Dynamic landscape changes in Glen Roy and vicinity, west Highland Scotland, during the Younger Dryas and early Holocene: a synthesis

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Abstract

This paper introduces a special issue devoted to the sequence of events in and around Glen Roy during the Loch Lomond or Younger Dryas Stadial, the short but important cold period dated to between ~12,900 and 11,700 years ago, during which glaciers last expanded to occupy the Scottish Highlands, and during the subsequent transition to warmer conditions at the start of the Holocene. The Glen Roy area is internationally famous for the 'Parallel Roads', pre-eminent examples of ice-dammed lake shorelines which were formed during the stadial. What makes these shorelines unique, however, is their role as distinctive time markers, allowing the order of formation of landforms and sediments to be construed with unprecedented detail. Varved lake sediments preserved within Glen Roy and nearby Loch Laggan provide a precise timescale - the Lochaber Master Varve Chronology (LMVC) - for establishing the rates and timing of some of the events. This introductory paper first sets the geological context for those new to this topic, with a digest of key advances in understanding made between the nineteenth century and the publication of the LMVC in 2010. It then summarises the evidence and ideas that have emerged from new research investigations reported in this special issue for the first time, and which shine new light on the subject. Two final sections synthesise the new data and consider future prospects for further refinement of the precise sequence and timing of events. A major conclusion to emerge from this new body of work is that the ice-dammed lakes, and the glaciers that impounded them, persisted in the area until around 11,700 to perhaps 11,600 years ago. This conflicts with recently promoted suggestions that the last glaciers in Scotland were already in a state of considerable decline by ~12,500 years ago.

Keywords:
Younger Dryas; Glen Roy; ice-dammed lakes; varves; glaciofluvial sediments; tephra layers; rapid climate change

1. Introduction

This special issue of the *Proceedings of the Geologists' Association* is dedicated to new evidence concerning the sequence and timing of events in Glen Roy and adjacent valleys in the western Scottish Highlands during the Loch Lomond (Younger Dryas) Stadial, the final phase of glaciation in the region, and while the landscape adjusted to warmer climatic conditions at the start of the Holocene. Glen Roy is internationally renowned for a series of prominent ancient lake shorelines, the 'Parallel Roads of Glen Roy' (Figure 1), of immense importance to the development of glacial theory and history, after they attracted the attentions of such luminaries as Louis Agassiz, Charles Darwin, Thomas Jamieson and, more recently, Brian Sissons. Visually impressive these palaeo-lake shorelines may be, but their real scientific value lies in the fact that they constitute isochronous marker horizons that allow the pattern of local glacier advance and decay, as well as the relative order of formation of associated landforms and sedimentary deposits, to be reconstructed in unprecedented detail.

The general geological context for the features and concepts discussed in this issue is as follows. The last great ice sheet to cover most of Britain and Ireland reached its maximum extent ~27,000 years ago (27 ka), after which it progressively declined until most of the British Isles, including much of Scotland, were ice-free by ~14 ka (Clark et al., 2012). This trend was reversed, however, when glaciers subsequently readvanced in the Scottish Highlands during a short cold period locally termed the Loch Lomond Stadial (LLS): the consequent resurgence of glacier activity during this period is referred to as the Loch Lomond Readvance (LLR). The LLS and LLR were, however, the local impacts of a more widespread climatic perturbation, referred to as the Younger Dryas Stadial (see Lowe and Walker, 2015), dated in a stratotype sequence in Greenland to between ~12.9 and 11.7 ka (Rasmussen et al., 2014). The iconic 'Parallel Roads' of Glen Roy, which mark the former surface outlines of glacially-dammed lakes, were formed during this period, but the exact age of their formation, and hence of the glacier advance that led to their impoundment, is a matter of continuing debate, and a key theme throughout this special issue.

In section 2 of this synthesis paper, we provide an outline of some of the key milestones reached in previous investigations into the glacial and environmental history of the Glen Roy area. This is followed in section 3 by a digest of the main findings of more recent field investigations, the results of which are reported for the first time in this special issue. In section 4, these new results are integrated to develop a revised model and timeline for important stages in the evolution of the landscape of this area, while the wider implications of the data are also considered. The collective evidence reported here has important bearing on arguments regarding the timing of the maximum extent and retreat of the last glaciers to occupy the Scottish Highlands in general. In the final section, some remaining scientific puzzles and limitations are explored, which are offered as potential targets for future research.

For those unfamiliar with the region and/or this topic, Figure 2 provides an essential geographical perspective, not only for following the discussions in this introductory paper, but also for linking the evidence presented in the other papers contained in this issue. A potential complication with the chronology of events considered here is that the evidence has been derived using several different dating methods (radiocarbon; surface exposure dating; varve chronology; ice-core years) with different baseline years. To simplify matters, all ages reported here have been converted to calendar years (base-line year zero), and expressed as ka (thousands of years before present), except where indicated.

2. Background: previous research

2.1 *19th century observations*

Although the Parallel Roads of Glen Roy were widely publicised from the early eighteenth century onwards, it was not till Charles Darwin visited the area and published a paper in the Philosophical Transactions of the Royal Society in 1839 entitled '*Observations on the Parallel Roads of Glen Roy, and of other parts of Lochaber in Scotland, with an attempt to prove that they are of marine origin'*, that serious scientific interrogation of their origins increased (Rudwick, 2017). Just one year after Darwin's speculative paper was published, Louis Agassiz visited Glen Roy during his influential tour of Britain which helped to foster the then embryonic 'glacial theory'. Agassiz was immediately struck with the remarkable similarity between the Parallel Roads and associated landforms in Glen Roy and adjacent Glen Spean (Figure 2) and features associated with ice-dammed lakes that he had observed in his native Switzerland, and proposed that they shared the same origin. Although this seed was sown, it was not till 1863 that T.F. Jamieson (1863) identified all of the outlet cols that controlled the lake levels and linked them to the local glacial evidence. He deduced that the distribution of the lake shorelines would signal the position of the ice fronts holding back the lakes, and argued from the freshness of the features that they must represent the final phase of glacial activity to have affected the region (Figure 3). However, Jamieson's initial observations were made before the first Ordnance Survey map for Glen Roy was published in 1873, which Joseph Prestwich (1879) was able to employ when exploring the nature of the surfaces of the Parallel Roads. Prestwich noted that the surfaces of the shorelines were not uniform, but varied in elevation by up to ~5m, and argued that the deformed nature of the Road surfaces suggested they were formed during an earlier glacial phase, not the final glacial episode. This prompted Jamieson to return to Glen Roy to re-assess the nature of the Roads by comparing field observations with the 1873 O.S. six-inch topographic maps. The results led him to conclude that the heights of the 'Roads' were not as variable as Prestwich had claimed, but that anomalous values reflected inconsistency in the precise positions selected by the survey officers for surface elevation measurement and failure to take into account the intermittent development of peat cover on the Road surfaces (Jamieson, 1892). Jamieson recognised the need for a more detailed and systematic instrumental survey of the shorelines that took such factors into account, a call that remained unheeded until J.B. Sissons took up the challenge some 80 years later.

2.2 The 'Sissons Model' of the sequence of glacier and lake adjustments

Between 1977 and 1983, Sissons (latterly with R. Cornish) published the results of a series of detailed investigations of the late Quaternary history of Glen Roy and vicinity (Sissons 1977, 1978,1979a, 1979b, 1979c,1981a, 1981b; Sissons and Cornish 1982a, 1982b, 1983). The work was based on landform mapping at either the 1:10,000 or 1:25,000 scale coupled with accurate levelling of points closely-spaced along the Parallel Roads, along a number of fluvial terraces that occupy parts of lower Glen Roy and Glen Spean, and over the surfaces of adjacent gravel fans and glacial landforms. This collective body of information laid the foundations for the mapping of the Loch Lomond Readvance ice limits in the area and for interpretations of the mode and timing of the formation of the Parallel Roads, assessments that are still largely accepted today and which we term the 'Sissons model'. In accord with the view expressed by Jamieson, the 'Roads' are attributed by Sissons to the action of ice-dammed lakes created by the last glaciers to occupy the area - during what is now defined as the Loch Lomond (Younger Dryas) Stadial (LLS/YDS). Some of the key conclusions arising out of this body of work are summarised below, to provide essential background for those not familiar with the area or topic. Further details are provided in the introductory paper by Sissons (2017a) included in this issue.

In summary, the sequence of events leading to the formation and abandonment of the ice-dammed lakes and Parallel Roads are as follows (key features are illustrated in Figures 3, 4 and 5, but also consult Figure 2 for some named locations).

- Glacial ice built up and advanced predominantly from the Ben Nevis mountain range and the mountains to the west of the Great Glen, and invaded lower Glen Spean, eventually forming a competent barrier to westward-flowing drainage (position A in Figure 3).
- This created a lake within the Spean-Laggan valley which extended all the way to the Laggan-Spey drainage divide, where the lowest point is a col at an altitude of 260 m (Figure 4).
- The lake escaped eastwards over this col into the catchment of the River Spey, while the flow of the Pattack River, which today flows south to the north-eastern shore of Loch Laggan, was reversed towards the Spey.
- It follows, therefore, that the surface altitude of the ice occupying the Great Glen and lower Glen Spean must at this time have been considerably higher than 260 m, to prevent lake waters escaping westwards.
- The 260 m lake also extended into lower Glen Roy, as far as the Turret-Roy confluence.
- Ice also blocked the mouth of Glen Gloy, which runs parallel to Glen Roy, forming a lake that overflowed a col with an altitude of 355 m, the lowest point on the Gloy's watershed with the Glen Turret catchment.

- Subsequently, further advance of the ice into lower Glen Roy blocked the confluence of the Roy and Spean (ice limit B, Figure 3), causing the lake waters within the unglaciated sector of Glen Roy to rise to the next lowest available outlet, a col situated at an altitude of 325 m within the tributary valley Gleann Glas Doire (Position 8, Figure 3; Figures 4 and 12A).
- Water flowed over that col and descended to enter, near Roughburn in Glen Spean, the 260 m lake that continued to occupy the Loch Laggan basin, the level of which was still maintained by the col beyond the present eastern margin of Loch Laggan (Figures 4 and 15).
- Yet further encroachment of the ice into Glen Roy, to its maximum position which is marked by a massive accumulation of glacigenic sediment (ice limit C, Figure 3), blocked the Gleann Glas Doire escape route, raising the level of the lake in Glen Roy to the next available overflow, the 350 m col at the head of Glen Roy (Figure 5).
- At this time, the ice in Glen Spean merged with glaciers descending the Laire and Treig valleys, outlets for ice sourced in the Ben Nevis Range and Rannoch plateau respectively. Lateral and terminal moraines mark the easterly maximum and, close to Roughburn, Glen Spean, outwash deposits built a prominent delta into the western margin of the 260 m lake that continued to occupy the Laggan basin (Figures 4, 5 and 15).
- A separate glacier also sourced from the Rannoch plateau occupied the Ossian valley, its meltwaters accumulating sediment in a delta (the Moy Delta) as they entered the 260 m lake (Figures 5 and 15A).
- The ice in lower Glen Roy was also forced into a small tributary valley of the Roy, named Caol Lairig, the terminus of which is marked by a prominent moraine close to the watershed that separates Caol Lairig from the Roy valley (Figures 5, 12).
- This three-fold sequential increase in lake surface altitudes within Glen Roy and its tributaries, the consequence of progressive ice advance, is termed the '*rising sequence*' of palaeo-lake shorelines.
- At the termination of the Loch Lomond Readvance, the ice in the Spean Valley disintegrated, its surface declining and its margin retreating down the Roy valley towards the vicinity of Spean Bridge (Sissons 1979b; Sissons and Cornish, 1983).

- This process initially led to the re-emergence of the col at Gleann Glas Doire, which allowed the lake level in Glen Roy to subside to 325 m again, while further retreat of the ice enabled the lake waters to escape down the lower Roy valley to re-join the 260 m lake in Loch Laggan.
- This descending series of lake levels is termed the '*falling sequence*'.
- Final drainage of the ice-dammed lakes in the Roy-Spean catchment is attributed to a catastrophic flood or 'jökulhlaup' (Sissons, 1979c; 1981b; Russell et al., 2003), evacuation of the water being channelled by a subglacial tunnel valley through the Loch Lochy basin towards Fort Augustus and thence onwards to Loch Ness, from where it could debouch into the North Sea (Figures 4 and 5).
- Sissons (1979c) calculated that the 260m lake in the descending sequence attained a volume of 5 km^3, occupying the middle and lower sectors of Glen Roy, the Loch Laggan basin and a large part of Glen Spean. The waning ice at some stage would have lost the competence to hold back such a body of water, with catastrophic drainage an inevitable result. Sissons (1979c) estimated possible maximal flow of water during initial outpouring to be about 22,500 $m^{-3}s^{-1}$, followed by several lower magnitude flood events as the ice mass progressively diminished in size and the Spean-Roy lake intermittently emptied.

2.3 *Gravel fans of Glen Roy*

While the above overall sequence of events and the pattern of glacial advance and retreat are generally accepted, the interpretation of other elements in the landscape have proved rather more contentious. For example, the middle and upper parts of Glen Roy contain a series of very large gravel fans, all but one of which occur along the flanks of the main valley but with apices at the mouths of tributary valleys (see Cornish, 2017). The one exception is the Glen Turret Fan that is spread across the Turret-Roy confluence, and which appears to be associated with arcuate moraine ridges along its inner margin. Sissons and Cornish (1983) attributed fan formation to debris-charged streams, in particular the 260 m lake, with which a number of fan surface remnants accord in altitude. By contrast, Peacock (1986) examined sedimentary exposures in this and several of the other fans in Glen Roy and came to the conclusion that they had been deposited subaerially (see also Peacock & Cornish, 1989).

Furthermore, Peacock (1986) assigned the formation of the fans to a retreat stage of the Late Devensian (Last Glacial Maximum or Dimlington Stadial) ice sheet, whereas Sissons favoured formation during the Loch Lomond Stadial. The age of the Glen Turret Fan is particularly controversial, since Sissons considers this fan and its associated arcuate moraine ridges to mark the terminus of ice that was forced up the entire length of Glen Gloy and over the 355 m col (Figure 5). Boston and Lukas (2017) disagree: on the basis of reconstructed glacier margins and inferred equilibrium line altitudes for the Monadhliath Mountains and uplands to the north of Glen Turret, they arrived at the same conclusion as Peacock, that glacier ice did not reach the Turret Fan during the Loch Lomond Stadial. On the other hand, mapping of glacial features in the Carn Dearg upland (Fig. 4) led Benn and Evans (2008) to conclude that Loch Lomond Readvance ice extended to the inner margin of the Turret Fan, in agreement with Sissons except for their proposed source of the ice. These interpretations (summarised in Table 1) and the evidence on which they are based are considered further below and in several contributions to this issue.

2.4 *Formation of the Parallel Roads*

A prominent lake shoreline with an altitude at 355 m is evident in Glen Gloy (Figure 3). It can be traced almost continuously throughout much of the length of the valley from the watershed with the Turret catchment south-westwards to within 3 km of Glenfintaig Lodge, close to where Glen Gloy opens out into the Loch Lochy basin (D in Figure 3). It had long been assumed that the 355 m lake was formed during the maximum intrusion of Loch Lomond Readvance ice into Glen Gloy, its waters spilling over a 355 m col into the contemporaneous 350 m lake that occupied the Roy and Turret valleys. This was the interpretation initially adopted by Sissons (e.g. 1978, 1979a), and illustrated in Figure 3 (ice limit D), but which he later revised on the basis of more comprehensive mapping of the area. His alternative hypothesis is that glacier ice advanced up the whole length of Glen Gloy, surmounted the col at the head of the valley and descended to the inner limit (north-western flank) of the Turret fan (e.g. Sissons and Cornish, 1982, 1983). This interpretation and the basis for it are examined further below, and also feature in discussions in several other contributions. Under this hypothesis, the 355 m lake would have formed while the ice was vacating Glen Gloy, which presumably was a relatively short period. This raises questions about exactly when and how these glaciolacustrine shorelines in both Glens Roy and Gloy were formed.

Sissons (1978) conducted a detailed analysis of the shorelines in Glens Roy, Gloy and Spean, accurately measured their width and angle of outward slope at 787 points and estimated the width of material removed during their formation (termed road 'volumes') at 236 points. In line with Jamieson's (1863, 1892) observations, Sissons considered the most likely mode of formation of the roads to be erosion of the valley back-wall and deposition on the front (the former lake shore), and derived geometrical calculations of the amount of valley-side material removed. Key points to emerge from the measurement data were that (a) road widths are strongly inversely correlated with hill-side slopes and (b) road volumes are unrelated to hill-side slope or to local geology, but are strongly correlated with length of fetch (wind and waves) from the south-west. On the basis of these observations, he concluded that the Roads were unlikely to have been formed by wave action alone, but excavation was aided by intense frost action, a process that may have been accelerated by frequent wetting and drying around the lake perimeter. The backing cliffs and shorelines tend to be best developed on slopes facing towards SW, which indicates that the process of shoreline formation was wind-assisted. However, away from these locations, the Roads are remarkably uniform in their development throughout large stretches of their tracks. Average widths for the top, middle and bottom shorelines in Roy and for the 355 m shoreline in Glen Gloy for tracts that lie beyond the maximal limits of the Loch Lomond Readvance are 11.3, 10.6, 10.1 and 10.0 m respectively. The shorelines do, however, extend into areas previously occupied by Loch Lomond Readvance ice, and presumably were formed while the ice was retreating and disintegrating. Corresponding average road widths for shorelines that lie within the areas formerly occupied by LLR ice are 9.4, 9.4, 11.7 and 9.8 m respectively. According to Sissons (1978, p. 244), these overall data "…appear explicable only if each road was at first formed extremely quickly and, thereafter, developed very slowly". This in turn raises two questions about their mode of formation: (i) over what time period did they develop? And (ii) do they mainly form in the rising or falling lake sequence? Analysis of varved sediments in the area, summarised next, potentially provides some answers.

2.5 *The Lochaber Master Varve Chronology (LMVC)*

Exposures of laminated lake sediment in Glen Roy have long been observed, and their potential as annually-deposited layers (varves) postulated (e.g. Sissons, 1979b; Peacock, 1986; Miller, 1987; Ringrose, 1989; Peacock & Cornish, 1989). A major advance was made, however, when the deposits could be examined using micromorphological techniques (Figure 6), and evidence for seasonal and annual deposition confirmed (Figure 7; Palmer et al., 2010). Microscale analysis was conducted on varved sequences exposed on the surfaces of two fans in Glen Roy and on a much longer series of submerged varves recovered from a borehole located near the eastern shore of Loch Laggan. Matching between these individual varved series was based on detailed measurements of variations in varve thickness and structure, combined with common marker features, such as distinctive sand layers or severely contorted laminae (Palmer et al., 2010). The integrated results provided, for the first time, an indication of the minimum length of time that the lakes existed, and in which the Parallel Roads were fashioned: 515 years (Figure 7).

Initially it was considered that the dominant control over variations in varve thickness was the distance between the ice front and the point in the basins at which the varves were being deposited, and on this basis Palmer et al. (2010) proposed the relative timing of the main changes in level of the lakes. From this information, it was considered possible to estimate rates of glacier advance and retreat, as well as the approximate amounts of time each of the Roads was subject to erosion during the rising and falling lake sequences. Subsequent research based on new varved records (reported in Devine and Palmer, 2017) suggests an alternative control on varve thickness variations, discussed in section 3, which invalidates the above assumptions. At present, therefore, it is not clear how long it took for each of the Roads to be cut, especially in the case of the 260 and 325 m shorelines within Glen Roy, which would have been subject to erosion during both the rising and falling lake sequences.

When first published, the LMVC was essentially a floating chronology (Palmer et al., 2010), although three observations suggested that the complete series was likely to have accumulated during the late Loch Lomond Stadial. First, visual matching of cyclic variations in the LMVC with oscillations in the Greenland ice-core records suggest an age span for the

LMVC of between ~12.25 and 11.61 ka (Palmer et al., 2012). Second, independent assessment of the age of the Road surfaces based on surface exposure dating give an age range between ~11.9 and 11.5 ka (Fabel et al., 2009), while a more recent application of this method suggests an age for the 325 m shoreline of 12.3 ± 0.8 ka (Small and Fabel, 2015). The third observation, which is more speculative, is the dramatic rise in varve thickness from about varve 460 in the LMVC (Figure 7) upwards, which could reflect the influence of Holocene warming conditions, the onset of which dates to ~11.7 ka (Walker et al., 2008). New evidence relating to the age of the LMVC is discussed in section 3.4 of this paper.

2.6 *After lake drainage*

As the LLR ice mass disintegrated and lake levels fell, fluvial action modified the various landforms (fans, moraines, kames and other glaciofluvial deposits) by creating a staircase of terraces progressively graded to lower base levels. Sissons (1979c) and Sissons and Cornish (1983) levelled a number of these terrace fragments throughout the Roy and Spean valleys and generated a number of height-distance diagrams which provide useful information on the sequence of events following glacier recession and lake lowering. In the upper Roy, the river initially flowed into the shallow northern extremity of the 260 m lake, removing and spreading gravels to form a gently-sloping valley floor. Following the sudden lowering of the 260 m lake, the River Roy incised into this smooth surface, creating a complex series of terraces and bluffs (Sissons and Cornish, 1983). Instrumental levelling of the terraces in the lower Roy and Glen Spean indicates that, following the evacuation of the 260 m lake, progressive lowering of lake level was intermittently halted allowing temporary lake stands in Glen Spean with surfaces at 113, 99, 96.5 and 90.5 m (Sissons, 1979c). Fluvial terraces are absent from a large (2 km-long) sector of Glen Spean which is occupied by kames and other ice-decay features, suggesting that large masses of stagnant ice occupied parts of the lower ground during the process of ice and lake evacuation. Another mass of stagnant ice features are congregated in the area to the south of Tulloch (Figure 3), with some of the hollows accumulating Holocene lake sediments and peats, the earliest sediments providing limiting ages on the demise of the ice and the ice-dammed lakes, a point developed in section 3.

2.7 *Deformation of the shorelines and lake sediments*

Instrumental levelling of the shorelines within Glen Roy has vindicated Prestwich's observation (1879) that they do not have uniform altitudes or tilts, but have been dissected into a series of blocks that have been differentially modified: some blocks show no detectable surface tilt whereas others may have gradients of up to 4.6 m km^{-1}, but tilt in different directions (Sissons and Cornish, 1983). The 350 m shoreline varies in complex fashion between altitudes ranging from 349.5 to 351.9 m, the 325 m shoreline undulates between 324.5 and 326.8 m and the 260 m shoreline between 260.1 and 262.4 m. Major rockfalls and landslips occur throughout Glen Roy and vicinity, and could be considered the cause of this fragmentation of the shorelines. However, Sissons and Cornish (1982a) proposed that one of the most severely dislocated blocks, on which the shoreline fragments have been uplifted by up to 3 m above normal shoreline altitudes, is closely associated with a major fault, and is more likely to reflect crustal deformation. They conclude that such crustal deformation may well have been triggered by catastrophic lake drainage, because the deformation clearly followed construction of the roads, yet the earliest fluvial terraces formed in the upper Roy soon after lake lowering are not dislocated, and hence the deformation is likely to have occurred immediately after the catastrophic lowering of the 260 m lake and before fluvial deposition along the valley profile (Sissons & Cornish, 1982a).

Chen (2012) has also measured the altitudes of the Road surfaces in the middle and upper parts of Glen Roy at 21,609 different locations, not by instrumental field survey, but by remote sensing, using NEXTMap digital elevation model (DEM) data. His results accord with those of Sissons and Cornish in many respects, especially concerning the large off-sets in Road elevations close to major landslips. He found, however, that the degree of deformation of the Road surfaces is much more complex than previously thought. Key observations that emerge from his new data include:

- The style of deformation can vary over short distances between arching or warping, block dislocation (vertical movements without tilting) and tilting
- The direction of tilting can have opposite gradients on adjacent stretches and even on the same measured short stretch of shoreline

- Maximal scales of dislocation appear to have been associated with former ice-marginal positions and/or landslips, especially close to major rock slope failures and entrenched gullies
- The pattern of deformation on vertically aligned stretches of the three shorelines can have different slope trends, and therefore appears to reflect changing deformation forces over the life-span of the three shorelines
- Despite the complexity of the DEM data, the shorelines appear to show regional-scale gradients, from SW to NE along the whole length of the shorelines, on which localised more severe dislocations are superimposed.

The evidence suggests the operation of more than one deformation process, and that these appear to have been continually changing over the period in which the shorelines were forming, possibly due to at least four interacting processes:

- the action of lake ice, which may have been particularly effective due to the abundant cleavages and bedding planes that characterise the local Dalradian metamorphic rocks;
- upward displacement of near surface rock layers by hydrostatic pressure in joints and clefts, exacerbated during freeze-thaw cycles;
- compression of near-surface layers of rock, caused by the weight of the advancing glacier ice and of the lake bodies they impounded
- the effects of catastrophic drainage by jökulhlaups, leading to sudden hydrostatic unloading and stress release.

His evidence sows considerable doubt about the possibility of ever establishing the precise original mean altitudes of the former lake surfaces, due to the scale and complexity of the deformation that the shorelines have been subjected to.

Examination of exposed laminated sediments within Glens Roy, Gloy and Spean led Ringrose (1987, 1989a; Davenport and Ringrose, 1987) to identify two particular episodes of deformation which he attributed to palaeo-seismic events. The first event was recognised by fault grading, incipient slump folds and ball-and-pillow structures in laminated deposits, evidence of pervasive liquefaction. The most severe deformations are associated with a zone that extends from Upper Glen Gloy into middle and lower Glen Roy and Glen Spean. There appears to have been a period of quiescence afterwards, identified by a series of about 20 undeformed laminae/varves, before the impact of a second deformation event that led to similar liquefaction structures, in places destroying or disturbing the evidence for the first deformation event. The first event was attributed to an earthquake caused by reactivation of the fault which runs through Roy and Gloy that is referred to in Sissons and Cornish (1982), and is thought to have occurred before drainage of the 260 m lake in Glen Roy and the 355 m lake in Glen Gloy. The second event was attributed to a second earthquake. Ringrose et al. (1991) consider the Roy-Gloy fault to be one of several late Quaternary ruptures in the Scottish Highlands that were nucleated along NNW-striking Caledonian structures and initiated by transient glacial ice-load flexure stresses, probably aided in the case of the Roy-Gloy rupture by a pore-pressure head induced by deep lake water.

2.8 *National and international importance of the Glen Roy landscape*

As the earlier parts of this section have demonstrated, the landscape of Glen Roy and vicinity is unique in the British Isles and very special globally. It is not simply because of the magnificent Parallel Roads, stunning in appearance though they may be. It is the way they interlink with a range of other landforms and deposits, including glacial moraines, kame terraces, kames and kettles, gravel fans, delta fans, fluvial terraces and landslips, to provide insight into the processes that shaped the landscape and a detailed narrative of the order in which events took place, something that is critical for understanding the ways that landscapes adjust in cool temperate upland regions. Additional piquancy is provided by the Lochaber varve chronology, which provides a bounding timeframe of high temporal resolution for this narrative, and by the evidence for an enormous lake burst (jökulhlaup), that connects events in Glen Roy with the Great Glen and Loch Ness. The picture is a complex one, difficult to portray in the space permitted here, but two introductory papers provide some amplification. Rudwick (2017) recounts evolving 19th century ideas about the mysterious Parallel Roads which were promoted by, for example, Lauder (1821), Darwin (1839), Agassiz (1840) and Jamieson (1863). Rudwick's paper illustrates the seismic change in geological thinking at the time, as the glacial theory, initially dismissed, eventually gained widespread acceptance by the end of the century, a conversion that influenced Darwin, and one in which the evidence from Glen Roy played no small role. In the second introductory paper, Sissons (2017a) develops his own model of the sequence of events in Glen Roy during the Loch Lomond (Younger Dryas) Stadial, providing more detail on the close interconnection between glacier and lake changes in the area. His paper also provides a useful prelude to some of the controversial issues aired in later contributions to this special issue, for example regarding the age of the gravel fans in Glen Roy, and of the Turret Fan in particular (see Boston and Lukas, 2017; Cornish, 2017; Lowe et al., 2017). Other syntheses of the glacial evidence in Glen Roy and vicinity can be found in two recent Field Guides published by the Quaternary Research Association (Peacock and Cornish, 1989; Palmer et al., 2008), while a third features in the 1993 Geological Conservation Review of the Quaternary of Scotland (Gordon, 1993).

The third introductory paper (Brazier et al., 2017) addresses an important cognate consideration, and that is the long-term custody and conservation of the landscape in and around Glen Roy. In an age when there is growing clamour for building space to satisfy demands for more housing and expanding economic endeavour, including agroforestry, wild open spaces are increasingly coming under pressure, a fever from which Glen Roy is not immune. Brazier et al. (2017) outline the efforts that have been made to preserve and publicise Glen Roy's unique landscape for the benefit of future generations, whether for geotourism, educational or scientific purposes. These efforts operated through a loose regulatory framework until the 1950's when Glen Roy was accorded the status of *National Nature Reserve* (NNR), managed by *Scottish Natural Heritage*, and designated a *Site of Special Scientific Interest* (SSSI), affording it protection from intended forestry plantation. In recent years there has been a growing undercurrent of discussion concerning retention of Glen Roy's NNR status, which has caused some local alarm, brought to the public's attention by *Lochaber Geopark*, a voluntary group which has received funding support from the *European Community*. We hope that the contents of this special issue will help to underline the national and international importance of this NNR: it will illustrate how the geological significance of the area is not confined to the classic views of the Parallel Roads within Glen Roy, for these features are merely the central component of a wider glacier land system that extends into Glen Gloy, Glen Spean and the Loch Laggan basin. Just as the heart cannot be studied in isolation from the arteries and circulatory systems that it serves, so too the

Parallel Roads cannot be fully understood in isolation from their wider Lochaber geological context. Furthermore, much remains to be explored and learned about the precise sequence and timing of events in this locality, which can have important implications for understanding the impacts of the Loch Lomond Stadial climatic downturn on Scotland as a whole. It is therefore vital that the landforms and sedimentary sequences with which Lochaber is adorned are preserved for posterity, and remain accessible for future scientific interrogation. The area's capacity to deliver new scientific discoveries is illustrated in eight of the papers contained in this special issue, and it is to these new developments that our attention now turns.

3. New developments pertaining to the evolution of the landscape of Glen Roy and vicinity

3.1 Introduction

The new evidence presented in this section addresses three broad themes relating to the evolution of the landscape of Glen Roy and vicinity: the age and origin of the major gravel fans in middle and upper Glen Roy; the local limits of Loch Lomond Readvance ice; and the timing and duration of formation of the lakes and associated landforms, and of their subsequent modification. Each of these themes is examined in turn, before a synthesis and evaluation of the collective results are presented in section 4. Figure 8 provides some locational orientation for the detailed discussions that follow.

3.2 *The age and origin of the gravel fans in Glen Roy*

Cornish (2017) presents the results of the most detailed examination undertaken so far of the major fans that occupy the upper (Glen Turret, East Allt Dearg, Canal Burn, Burn of Agie, Allt Chonnal fans; Figure 9) and middle (Allt Bhreac Achaidh, Brunachain and Reinich fans; Figure 10) parts of Glen Roy, based on morphological mapping and examination of exposed sediment sections, allied to comprehensive instrumental levelling of the fan surfaces and of the terraces that cut into the fans. The latter reveal that the fans have been subject to extensive post-formational dissection. Cornish provides information on the pre-dissected configuration of the fans and estimates their original sediment volumes. The principal conclusions he draws from these new data are:

- All of the fans, including the Turret Fan, were deposited into former proglacial lakes held up by glaciers during the Loch Lomond Stadial;
- Excluding the Turret fan, the largest gravel fans were deposited in the shallow heads of the 260, 325 and 350 m lakes, infilling the lakes to the extent that gravel deposition was in part subaerial;
- The absence of foreset bedding and cross and ripple-drift bedding from the deposits reflects the relatively shallow depth of the lake waters, which inhibited development of classic Gilbert-type deltas but encouraged deposition in the form of Hjulström-type fans, which form under extremely high sediment discharge;
- A consistent three-fold lithostratigraphic sequence of gravel/lacustrine sediment/gravel is observed in exposures in the fans in upper Glen Roy, which Cornish attributes to an initial phase of deposition of thick gravel (at least 20 m) during the rising lake sequence, which gave way to finer lake deposits as the lake levels deepened, and these in turn are covered by a capping layer of attenuated gravel deposited during the falling lake sequence.

Fan development, and the nature of the material deposited, therefore depended on lake water depth, and the fan location determined the time of maximum input of gravel. Hence the fans in middle Glen Roy received most gravel input during the 260 m lake stand; when lake levels rose, smaller perched fans/deltas developed at the lake margins, while subaqueous fans and finer suspended material accumulated in the deeper water. At the same time, copious gravels were being deposited in the higher lake margins in upper Glen Roy, for example forming the Allt Chonnal fan during the 325 m and 350 m lake stands. Cornish's calculations show that previous assumptions of limited gravel accumulation at the mouth of the Allt Chonnal are erroneous, for some 6,000,000 m^3 of gravels were deposited in this locality during the time span of the LMVC.

Crucially, Cornish argues that in order to generate this amount of gravel so quickly, and to form fans of such magnitude, glaciers must have existed in upper Glen Roy during the Loch Lomond Stadial, this being the most likely source of rapid sedimentation. He therefore rejects previous suggestions by Peacock (1986) and Boston et al. (2013) that some or all of these fans were formed in pre-Stadial times, i.e. during the waning stages of the Late Devensian ice sheet. Part of his rationale for arriving at this conclusion, however, rests on reassessment of the extent of glaciation in and around Glen Roy, the topic addressed next.

3.3. *Loch Lomond Readvance Ice limits in Glen Roy and vicinity*

Attention has already been drawn in section 2 to the thorny issue of the age of the Turret Fan, and of the terminal moraines with which they are associated. This particular feature is also the focus of attention in several of the papers included in this issue (Table 1), and actually is emblematic of a wider problem concerning the overall extent of glacier ice within the Lochaber district during the Loch Lomond Readvance. While the limit of the Spean glacier's advance into Glen Roy (to near the Viewpoint) and of the Treig glacier's termination near Roughburn (Figures 5 and 15B) are clearly marked and are not contested, the limits of the ice in upper Glen Roy and on the uplands forming the Gloy catchment are not so well established. Nevertheless there is growing evidence that suggests more extensive glaciation in these areas than previously supposed.

Boston and Lukas (2017) have mapped the glacial features on the Carn Dearg plateau, to the north and northeast of Glen Turret, and found evidence for a plateau icefield (Figure 11) that they assign to the Loch Lomond Readvance, and which they consider was connected to a more extensive icefield in the Monadhliath Mountains, further east (Boston et al., 2015). That there was LLR ice present in the Carn Dearg area is supported by Benn and Evans (2008) and Eaves (2009), though in both of these studies more limited glacial cover is proposed. An obvious contrast can also be seen between Figure 11 and Figure 5, and that is the extent of LLR glaciation in Glen Turret: Boston and Lukas (2017) find evidence for glacier tongues encroaching only into the northern part of the Turret catchment, while Cornish (2017) supports Sissons' (2017a) view that ice from Glen Gloy reached the Turret fan during the LLR. Benn and Evans (2008) also propose that LLR ice reached the Turret Fan, but from ice sourced on Carn Dearg, not Glen Gloy. Clearly, there is considerable disharmony between these four independent assessments of the geomorphological evidence (Table 1), except in the case of the valley of the Allt Chonnal, where three of the reconstructions envisage a glacier terminating at the apex of the Chonnal debris fan (Figure 9). This supports the view of Cornish (2017), that the fans in upper Glen Roy were probably glacier-fed.

Boston and Lukas (2017) reject a Loch Lomond Stadial age for the Turret Fan and associated moraine ridges on two main grounds: morphostratigraphic criteria, and regional ELA (equilibrium line altitude) trends. The former argument rests on the observation that glacigenic landforms of LLR age tend to be more sharply defined and more densely packed, especially when confined to narrow valleys, than deposits of pre-Stadial (Late Devensian ice sheet) age. The latter tend to be larger, more subdued and more widely spaced. It is true that the Turret linear moraine ridges are not sharp-crested, but Lowe et al. (2017) attribute this to the fact that these moraines were submerged beneath water up to 80 or 90 m deep at the time of the 350 m lake stand, and were probably scoured by the flood waters that would certainly have rushed over them during lake level fall, especially the decline from 325 to 260 m. Given this context, a morphostratigraphic approach may not apply in this instance. Cornish (2017) also argues for an LLR age in view of his observation that the surface altitudes and internal lithostratigraphic sequences of all of the fans in Glen Roy, including the Turret Fan, are intricately related to the 260, 325 and 350 m lake levels. He also points to evidence of several terraces, one of which is indented by a conspicuous kettle hole, that delimit a retreat stage of the retreating Turret glacier, associated with the 325 m lake level.

The second line of evidence proposed by Boston and Lukas (2017) stems from their ELA calculations obtained for the inferred LLR icefield over Carn Dearg, which range between 560 and 646 m. These are somewhat lower than the mean ELA value of 714 ± 25 m calculated for the Monadhliath icefield (Boston et al., 2015), though different catchments within the latter show a wide range of ELAs between 560 and 816 m over a west-east gradient. The Carn Dearg estimates compare reasonably well with the range of ELA values of 622-656 m obtained for reconstructed LLR ice cover in the West Drumochter Hills, which lie further south (Benn and Ballantyne, 2005), and with that of an isolated glacier that was nourished in Coire Ardair during the LLR, which lies only 12 to 15 km SE of Carn Dearg (Figures 8 and 15A). Jones et al. (2017) present a detailed map of the excellent LLR moraines preserved in Coire Ardair, and use the results to calculate the ELA of the LLR glacier at its maximum, as somewhere between 634 and 688 m. Given this spread of regional ELA values, Boston and Lukas (2017) argue that the elevation of the floor of the

Turret valley seems anomalously low compared with its neighbours on the Carn Dearg plateau, and hence considered the placement of an LLR limit at the Turret fan to also be too low. This argument only applies, however, if Carn Dearg is considered the only source of LLR ice within the Turret catchment, and if the Carn Dearg ELA values are representative of the wider region. If the ice was sourced from Glen Gloy, however, then the altitude of the floor of Glen Turret almost becomes irrelevant. After all, LLR ice invaded lower Glen Roy and the entrance to Caol Lairig at valley floor altitudes well below those of Glen Turret, and was thence forced up a reverse gradient into both valleys. Under the Sissons Model (section 2.2), ice advancing from the Great Glen and Ben Nevis Range would have entered the mouth of Glen Gloy long before it reached lower Glen Roy and Caol Lairig (Figure 5); whether it had the capacity to fill Glen Gloy and spill over into the Turret catchment would, however, depend on the altitude of the ice surface in lower Glen Spean, and the ice surface gradient, aspects that have not yet been investigated in detail. The ice contours shown in Figure 5 are approximations made by Sissons with little precise information on LLR glacier limits and their associated ELAs in the western Great Glen, and could well be under-estimates. Indeed, Cornish (2017) contends that there is geomorphological evidence to suggest that ice in the Great Glen during the LLR spilled into Glen Gloy, and speculates that the Monadhliath icefield was connected to ice in the Great Glen, and that therefore the regional ELA estimates for this icefield may not be typical for the wider Lochaber area. Clearly, the maximum extent of LLR glaciation in Lochaber presently remains a contentious topic.

By contrast, more certain detail can be added to the sequence of events in lower Glen Roy and Caol Lairig, courtesy of a recent study by Tye and Palmer (2017), where again the distribution of lake shorelines provides the key. As previously noted, LLR ice invaded Caol Lairig from the south, the maximum limit being marked by a prominent arcuate terminal moraine, located close to the col that separates this valley from that of the Roy (A in Figure 12B). The altitude of the lowest point on the col is 297 m. A suite of sedimentary deposits extends from the moraine southwards, which Tye and Palmer show to consist of subglacial tills and a complex sequence of proximal, distal and deltaic glaciolacustrine sediments. These accumulated as the ice progressively withdrew southwards from the limit. Lake shorelines are clearly marked at four levels, 260, 325 and 350 m, plus one that is unique to

Caol Lairig, at 297 m, this last presumably controlled by the aforementioned col. The distribution of the shorelines suggests the following relative order of events. During the falling lake sequence, the 350 and then 325 m lakes flooded into upper Caol Lairig, which means that the ice had receded to B (Figure 12B) before the ice had dissipated in lower Glen Roy. Furthermore, the evidence of the 297 m shoreline indicates that the ice in Caol Lairig had only receded as far as C in Figure 12B when the ice in Glen Roy had melted sufficiently to allow lake level to fall to 260 m. The 297 m lake in Caol Lairig could only exist after the lake level in Glen Roy fell below the 297 m col overflow. Tye and Palmer (2017) attribute the differential rates of retreat of the two ice lobes to successive alterations in the ratio of ice thickness to lake water depth. Questions remain, however, over the extent of the lake shorelines during the rising sequence, answers to which may be found in the sediments that underlie those currently exposed in Caol Lairig, details of which are provided in Tye and Palmer (2017).

3.4 *Timing and duration of events*

The chronology of events in the Glen Roy area has been touched upon in previous sections, but here we summarise additional new findings and considerations that have a bearing on this specific topic. First we focus on the age of the gravel fans, including the Turret fan, then on the Lochaber varve chronology, and finally on evidence relating to the time when, following the decay of the glaciers and evacuation of the lakes, slopes were stabilised by colonisation of local slopes by vegetation and by a significant reduction in sediment supply to the basins and river systems.

Immediately upstream from the inner margin of the Turret Fan is a basin which is enclosed by a rock step over which the River Turret currently flows. The basin was first investigated by Lowe and Cairns (1991), at a location named Turret Bank, with the purpose of determining the age of any preserved deposits, for if the Turret fan and associated moraines were formed at the time of the retreat of the Late Devensian ice sheet, then the basin should (in theory) contain a Lateglacial sequence – i.e. sediments of Lateglacial (Windermere) Interstadial age. None were found, for pollen-stratigraphical studies suggested the oldest fossiliferous deposits to be of early Holocene age. The results are considered equivocal, however, as an open gouge sampler was employed, and thus the sediments could be easily contaminated, while coring was conducted by hand, making penetration of the deeper, more consolidated sediments difficult. The possibility that sediments of Lateglacial Interstadial age lay buried beneath the sampled deposits could not be ruled out. In view of these limitations, this basin was reinvestigated and the new results are presented in this issue (Lowe et al., 2017). In this new study, mechanically-powered coring was adopted, using a fully enclosed sample chamber, and three lines of evidence point to the sediment sequence recovered from the basin having been wholly deposited during the Loch Lomond Stadial-early Holocene transition: pollen data reveal a sequence of vegetational changes that is typical for this transitional period; varved deposits preserved in the sequence appear to bear a strong resemblance to either mid or late Stadial varves in the Lochaber Master Varve Chronology; and a distinctive early Holocene tephra layer – the Askja-S Tephra – was discovered within the sequence. In view of these new data, Lowe et al. (2017) conclude that it is likely that LLR ice extended to the inner margin of the Glen Turret Fan, and that the fan was probably constructed by glacial meltwaters at this time, to explain the absence of a Lateglacial profile.

There could be other explanations why Lateglacial sediments were not detected in the Turret basin, which Lowe et al. (2017) acknowledge. For example, the early Stadial-Holocene transition sequence could be underlain by an impenetrable layer of peri- or paraglacial debris which has buried Interstadial sediments. But a number of other considerations make this seem unlikely. Figure 13 shows the locations of the nearest published Lateglacial sequences to the Glen Roy area: Loch Etteridge in the east (Sissons and Walker, 1974; Walker, 1975), Loch Tarff in the north (Pennington et al., 1972), Salen and several basins on the Arisaig peninsula in the west (Wain-Hobson, 1981; Shennan et al., 1996) and Pulpit Hill, Oban, in the south (Tipping, 1991). The area enclosed by these records was almost entirely covered by LLR ice, but Glen Roy stands out as an exception. It contains the extensive gravel fans - but why are these, as Cornish (2017) shows, so intimately related to the 260, 325 and 350 m shorelines? Peacock (1986) has argued that some of the fans formed subaerially, but as Cornish (2017) points out, that would require active glaciers in upper Glen Roy, while the lower Spean, adjacent to the Ben Nevis range, remained ice-free, allowing drainage to reach the Great Glen, which seems glaciologically unlikely. Furthermore, if the fans were formed in an earlier period, during ice sheet decay, then soils would have formed on their surfaces during the warm period that followed (the Lateglacial Interstadial), remnants of which might be expected to be preserved beneath the varved lake sediments that were deposited during the LLS. None has been found. The lack of any sign of pre-Stadial deposits is puzzling unless, as we surmise, all the glacial landforms and gravel fans in this area were formed during the Loch Lomond Stadial. This is the simplest explanation, and remains our favoured one, until robust evidence for an alternative is forthcoming.

The Lochaber Master Varve Chronology (Palmer et al., 2010, 2012) provides a timescale for events in the Glen Roy area following the initiation of the Glen Roy lake system, but new evidence suggests that additional sites with varved sediments remain to be discovered, offering new insights not only into their mode of formation, but also on the timing of events. Varved deposits are preserved in the basal sediments that accumulated in the Turret Bank basin, referred to above (Lowe et al., 2017), and are also on the surface of the Allt Bhreac Achaidh (ABA) fan (Figure 10; Devine and Palmer, 2017). Both sets of deposits include distal glaciolacustrine varves that resemble those preserved in the Glen Turret fan (GTF) series, offering the potential to key them into the LMVC. This is made difficult, however, by several hiatuses that interrupt the ABA record, probably caused by ice-rafted debris, by deformation of some layers or by the deposition of thick sand lenses, while the record of varve thickness variations in the Turret Bank sequence is incomplete. Nevertheless, these new discoveries are important in two respects. First, the hiatuses probably reflect ice-proximal processes. The ABA fan is much closer to the inferred LLR glacier terminus in lower Glen Roy and to the valley side than the GTF varve series, and hence was more exposed to disturbance. Equally, while the GTF series lies on the surface of the Turret fan, well away from valley sides and protected from melt processes associated with a receding glacier within Glen Turret, the Turret Bank site would have been fully exposed to these influences, which could explain the highly disturbed nature of the basal sediments at this site (Lowe et al., 2017). Second, examination of the varved deposits at ABA suggests that varve thickness changes mainly reflect distance from small tributary streams flowing across the fan surface as the main factor governing sediment supply (Devine and Palmer, 2017), rather than distance to the ice margins which were migrating within the glacial lake systems of Glen Roy, as previously assumed by Palmer et al. (2010).

This has a significant bearing on the application of the LMVC to the dating of lake and glacial ice-front adjustments.

Sissons (2017b) also questions the interpretation of one of the key features in the LMVC, and that is the marked change from very thin varves to much thicker varves after about 300 years of varve deposition (Figure 7). Palmer et al. (2010) considered that this transition was one of several that reflected the encroaching ice margin, and proposed that most of the varves were laid down during the rising lake sequence (a total of ~420 years). They also assumed two significant disturbance layers in the sequence (the sand bed at varve year 314 and deformed varves at around varve year 426 – Figure 7) to have been caused by seismic events associated with ice advance and retreat. These ice margin changes caused lake levels to rise and fall, affecting the loading on land surfaces and reactivating faults. Sissons (2017b) has proposed that the transition from very thin to thick varves at varve year 300 reflects a change from intensely cold conditions, when glaciers were advancing or stable, to more variable (stormy) conditions, when the glaciers started to recede. He attributes the sand bed to increased input of sediment following the fall in lake level from 350 to 325 m, and the layer of deformed varves to an earthquake triggered by the jökulhlaup that led to the emptying of the 260 m lake. Clearly, the finer details of the LMVC can be interpreted in different ways: for example Palmer et al (2012) ascribe variations in microfacies in the summer layers to increasing incidence of storms, a trend that started much earlier in the LMVC. Further research is therefore needed to resolve these differences in interpretation, a point we return to in the closing section of this paper. These difficulties notwithstanding, the overall total number of varves (515) is considered a robust *minimum* estimate of the duration of the lake system in the Spean-Roy-Laggan valleys: minimum, because it is not known how many varves are represented in the deformed layer, while it is also possible that deposition of the sand bed removed some layers.

A critical recent discovery with respect to the LMVC has been the detection of two cryptotephra layers (volcanic ash layers that are not visible to the naked eye) within the varved sequence, which anchor its chronology. The oldest occurs in the lower part of the series (tephra layer 120 from base) and has been assigned to the Vedde Ash, dated to ~12.17 ka in the Greenland stratotype record (Rasmussen et al., 2006) or with a mean age of

~12.02 ka, based on dated lake records (Bronk Ramsey et al., 2015). For present purposes we use a rough mean of these two estimates (12.1 ka) to define the age of the Vedde Ash, until the precise age of this isochron is better established. Using this approach, the onset of varve deposition dates to ~12.20 ka. The younger cryptotephra layer, recorded in varve layer 424 from base, has been assigned to the Abernethy Tephra (MacLeod et al., 2015). The absolute age of the latter tephra layer is not well established at present, but it is generally found close to the Stadial-Holocene boundary, and the best available estimate of its age places it between ~11.79 and 11.20 ka (Matthews et al., 2011). Its position within the LMVC, relative to the Vedde Ash, implies an age of ~11.77 ka, while the youngest varve layer in the LMVC, signalling the disappearance of the lake system, is estimated to date to ~11.68 ka (12.2 minus 515).

By ~10.83 ka the landscape had settled into more quiescent times, devoid of glacier ice and ice-dammed lakes, and with juniper-birch scrub adorning the local slopes. Two local records point to this conclusion. First is the evidence from the Turret basin site, referred to earlier. The glaciolacustrine deposits that were initially deposited in this basin give way conformably to organic lake muds which contain a pollen record that indicates the local establishment of juniper-birch vegetation prior to the deposition of the Askja-S Tephra (Lowe et al., 2017). At this point, the basin had almost infilled to the level of the rock bar that enclosed it, and a fluvial floodplain was established on the floor of the Turret valley.

The evidence from a second site is also telling. The site of Inverlair is located in a deep kettle hole that lies within an extensive suite of kame deposits south of Tulloch (Figures 3 and 15B). The kames were formed during the stagnation of the LLR ice that occupied the Loch Treig valley and the floor of Glen Spean (Figure 5), and contributed to the mass of ice that caused the lake levels in Glen Roy to rise to 325 m and subsequently to 350 m (Sissons, 2017a). Close to this locality is a major terrace with a surface altitude of 260 m, indicating formation during the retreat of the LLR ice. The Inverlair kettle basin contains nearly 12 m of infilled sediment, the lowermost deposits of which contain pollen assemblages showing a typical early Holocene succession of crowberry, followed by juniper and then birch (Kelly et al., 2017). Within the juniper phase, the Askja-S Tephra is recorded, an association that is in accord with that from the Turret Bank sequence. What is critical about the Inverlair kettle basin, however, is that the altitude of the bottom of this hollow lies ~100 m below that of the nearby 260 m terrace surface. The sediments investigated by Kelly et al. (2017) are fine gyttja/organic lake muds, typical of small lakes and ponds, that accumulated at a time when crowberry, juniper and birch were colonising the local slopes. This could only have happened after the 260 m lake had vacated the area, which in turn must have pre-dated the age of the Askja-S Tephra - 10.83 ka. How long before cannot yet be established, but we now have two robust limiting ages for the sequence of events examined in this special issue: ~12.2 ka for the initiation of the 260 m lake in the rising lake sequence, and 10.83 ka for the complete disappearance of ice and ice-dammed lakes from Glen Spean, and for the colonisation of the area by plants requiring stable soils and relatively warm conditions.

4. Synthesis

In this section we integrate the various lines of evidence reviewed in previous sections to provide an overview of the sequence of events in Lochaber between 12.20 and 10.83 ka and assess their implications in the wider context. We start with the key chronological record from this area, the LMVC (Figure 14). The spine of the LMVC template is the record from Loch Laggan East (location shown on Figure 15), which extends over almost the entire 515 varve years. Three other more curtailed records (from the surfaces of the Allt Bhreac Achaidh, Glen Turret and Burn of Agie fans) have been matched to the LLE record, and to each other, using trends in varve thickness measurements and sedimentary marker horizons. The credibility of the results can be gauged by independent tephrostratigraphical markers.

Figure 14 lists the series of tephrostratigraphic isochrons now recognised in Scottish sites, extending through the interval from the early Lateglacial Interstadial to the mid-Holocene, with their current best-estimate ages (after Timms, 2016). Six of these are registered in the Loch Etteridge lake sediment sequence, the nearest site to Glen Roy that extends back to the Lateglacial Interstadial (Figure 13). The Vedde Ash is recorded in the middle of the LLS clays in this sequence, which provides an isochronous link to varve year 120 in the LMVC. The Abernethy tephra, found in the Glen Turret fan varve sequence, provides a second isochronous link between the LMVC and the Loch Etteridge record: this tephra is always found close to the LLS/Holocene boundary (MacLeod et al., 2015), which supports the placement of the GTF varve sequence within the upper part of the Loch Laggan East record. The possibility that the Abernethy Tephra is also registered in the Turret Bank sequence is uncertain at present, but if verified, would help to cement these correlations (see Lowe et al., 2017). The Askja-S Tephra links the Inverlair and Turret Bank sequences, but it is unfortunate that there is a hiatus between the top of the varved sediments at Loch Laggan East, and the sampled Holocene sediments that contain evidence for 5 different Holocene tephra layers (MacLeod, 2008). The missing section could contain evidence for the Askja-S Tephra, which would add further rigidity to the scheme, and hence is an important target for future research. At present, however, the available lithostratigraphical, pollen-stratigraphical, tephrochronological and varve chronological records from the sites represented in Figure 14 are internally consistent, with the important conclusion that the Lochaber ice-dammed lakes were initiated about 12,200 years ago and persisted for around 515 years.

If correct, the LMVC template and the collective data reviewed in section 3 indicate a sequence of dramatic changes in the landscape of Lochaber over a period of around 1400 years. Table 2 provides a timeline of the key stages, most of which cannot be dated precisely, although the Parallel Roads give guidance as to the relative order of events. This timeline of events is shown in pictorial form in Figure 16, which also places the LMVC scheme in a wider context. The key thing to observe is how the age uncertainties provided by combined tephra and varve records are much more precise than those based on other approaches, such as the bulk sediment radiocarbon dates from Loch Etteridge and surface exposure ages. The additional potential that the LMVC offers for the future, however, is the possibility of dating precisely the changes that took place within the life-time of the glacial lakes. For example, if the length of time that the individual lakes existed during both the rising and falling sequences can be estimated, this in turn would provide time limits for the migration of the glacier margins that forced these changes. It has already been argued that the Turret and Caol Lairig glaciers probably advanced and retreated at different times compared with the Roy glacier (section 3.4; Table 2; Figure 16), and some of these changes must have occurred within perhaps as little as 100-200 years. There is no other site in the British Isles where the timescale for ice dynamics can potentially be reconstructed with this degree of finesse. The other exciting element to note is that different ice lobes of this glacial landsystem appear to have reached their maxima at different points in the timeline (Figure 16). For example, if the ice did advance through the Gloy-Roy col to the Turret Fan, then it was in retreat whilst the ice in lower Glen Roy was attaining its maximum. Likewise the retreat in lower Glen Roy and Caol Lairig also appears to be asynchronous over a decadal timescale.

The overall conclusion that the ice-dammed lakes in Glen Roy date to between ~12.20 and ~11.7 ka is, however, incompatible with model simulations which suggest that the LLR ice was at its thickest during the first 500 years of the LLS, and then progressively thinned as the climate grew more arid (Golledge, 2010), and with recent suggestions by Bromley et al. (2014) that LLR ice on the Rannoch Moor plateau disappeared from Rannoch Moor by as early as 12,500 years ago. Bromley et al.'s conclusion is based on a series of radiocarbon dates obtained from basal organic sediments that accumulated in several small lake basins at different locations on the Rannoch Moor plateau. It is a large data-set, meriting serious attention, yet it is difficult to reconcile their proposal with the LMVC scheme. For example, the Treig and Ossian glaciers (Figures 5 and 15B) were sourced from the Rannoch plateau and, as previously mentioned, contributed to the mass of ice that dammed the 325 and 350 m lakes in Glen Roy. Under the LMVC-based scenario, summarised in Figures 14 and 16 and Table 2, the large ice mass that invaded Glen Spean from the west during the LLR, as well as the Treig and Ossian glaciers, were still advancing sometime after 12,200 years ago, and did not start to retreat until ~11,925 years ago, the estimated age of the sand layer in the LMVC scheme which, according to Sissons (2017b), possibly reflects the demise of the 350 m lake.

These inferences based on the LMVC scheme have close parallels with those based on varved records from sites close to the southern shores of Loch Lomond, which also date the arrival of the maximum position of the Loch Lomond glacier, in the type locality for the Loch Lomond Readvance, to post-12.0 ka (MacLeod et al., 2011). Confirming that the records from both Glen Roy and Loch Lomond are reliably dated is vitally important, for the timing of local glaciation reflects the climatic forcing factors that affected Scotland at the time. This has an important bearing on understanding the course of events during the Loch Lomond Stadial, not only locally, but within the context of the North Atlantic climatic régime as a whole (Brauer et al., 2008; Bakke et al., 2009; Broecker et al., 2010). In this context we note that a recent review of the evidence for Younger Dryas glaciation in western Norway concluded that readvancing parts of the ice sheet reached their maximal extents at the very end of the YD, around 11.5 ka (Mangerud et al., 2015). This apparent similarity in timing between Scotland and Norway is intriguing, and serves to intensify the resolve to continue to probe the evidence in the Glen Roy area, to develop sterner tests of the stratigraphical relationships proposed above, and to refine still further the LMVC. In the final section that follows, we consider approaches that potentially could yield such dividends.

5. Future prospects

In the course of reviewing published and new information pertaining to the sequence of events in Lochaber during the final stages of the last glacial period, attention has been drawn to a number of problematic or uncertain matters that require further investigation. It is important to stress, therefore, that the scheme outlined in Table 2 and Figure 16 is not intended or regarded as definitive, but as an interim statement which might steer future research towards resolving key issues. There is ample scope for achieving progress in this regard, including further refinement of the chronology of events. Planned or potential activities might usefully focus on the following three approaches: extended and/or more intensive field mapping; diversification of the dating methods employed; and extending and refining the LMVC, while testing its reliability.

Concerning the first of these approaches, there is a clear need to extend detailed field mapping of LLR glacial landforms into the Great Glen and the northern margins of the Ben Nevis Range, in order to gain a clearer picture of ELA trends in the region. This may help to clarify the LLR ice margins in, and adjacent to, Glens Roy and Gloy, and the extent to which they were associated with the ice cover that has been proposed for the Carn Dearg plateau and Monadhliath Mountains (Boston and Lukas, 2017), while mapping of glacial deposits on the northern flanks of the Creag Meagaidh range might also confirm the possible glaciation of this area during the LLR (Finlayson, 2004, 2006). Equally, the model for the evolution of the gravel fans in middle and upper Glen Roy proposed by Cornish (2017) could be amplified in two ways. First, more detailed examination of the architecture and sedimentary characteristics of the lithological layers of which they are composed might clarify their precise relationships with potential gravel sources and the Parallel Roads. Second, reference has been made to a number of places where laminated lake sediments have been observed beneath, within and overlying the fan deposits. If these contain varved sequences, then it may be possible to key these into the LMVC, possibly allowing the ages of the fans to be determined, a programme of work that is already under way.

The debate about the age of formation of the gravel fans has been a prolonged one, and continues, because there is no straightforward means of dating them directly. Some attempt was made to use optically stimulated luminescence (OSL) dating methods, which is usually based on quartz grains, but the quartz in deposits from the Glen Roy/Glen Spean area was found to have too low a signal (Lowick and Bailey, 2008). However, more success was found with the application of infrared stimulated luminescence (IRSL) of feldspar grains obtained from sand layers in the Moy delta fan. The results suggested ages of 13.3 +/- 0.7 ka for the lower Moy deposits, and 11.4 +/- 0.6 ka for upper layers, which led Lowick and Bailey to suggest that the feature is polygenetic – i.e. initiated during the Dimlington Stadial, and further developed during the LLR. This conclusion is rather equivocal, however, given the uncertainties on the ages – they could just as well indicate formation of the whole of the delta fan during the LLR. Subsequently, significant technical improvements have been made in this dating method (Smedley et al., 2015, 2016), so that its further application to the dating of fans in Glen Roy and vicinity may prove rewarding, and is therefore to be encouraged. Presently, the only other way to date the fans is by indirect methods. One approach would be to establish the precise link between fan deposits and individual glaciolacustrine shorelines, and then date the shorelines using surface exposure dating (see section 2.5), but the errors on individual dates using this method are of the order of 1 to 2 ka, up to four times the overall period in which the entire sequence of the Glen Roy lakes were formed. By far the most precise method that is presently available for dating these features, therefore, would be by linking them into the LMVC, wherever possible.

There is much that can be done to improve and test the LMVC, however. As indicated earlier, new series of varves are being discovered within Glen Roy, which may provide additional checks on parts of the scheme. New corings into the sediments beneath Loch Laggan could also uncover longer and better resolved records of the entire varve sequence;

up till now, only the north-eastern margin of the lake has been explored. Furthermore, the tephra isochrons which anchor the timescale are based on rather low tephra counts (Palmer et al., 2010; MacLeod et al., 2015), and these need to be reaffirmed, while the age of the Abernethy Tephra needs to be better defined. The new discovery of the Askja-S Tephra holds out the exciting possibility of synchronising other sequences in the study area, for example the lake sequences found within depressions located on the overflow cols between Glen Gloy and Glen Roy (355 m lake), between Glen Roy and the River Spey (350 m lake) and in the Feagour Channel – the overflow for the 260 m lake to the east of Loch Laggan (Lowe and Cairns, 1991; Macpherson, 1978). Matthews et al. (2011) and MacLeod et al. (2011) have demonstrated how a combination of radiocarbon dating (based on terrestrial plant macrofossils) and tephrochronology can generate improved age models for reconstructing past environmental events, and this approach could be adopted at Inverlair, Turret bank and other basin sites to help constrain the LMVC still further.

A further potential test of the integrity of the LMVC scheme that could be explored is the degree to which it provides a basis for synchronising other elements of the landscape, not yet linked in. For example, the Coire Ardair LLR glacier (Jones et al., 2017) fed the Aberarder fan which has an apex at 260 m, and the Ossian glacier fed the Moy delta fan, which has a surface at 260 m and clearly formed during the life-time of the 260 m lake (Figure 15A). Both descend below the present surface of Loch Laggan, and may register signals within the Loch Laggan varve sequence. It is possible therefore that the ages of the start and termination of these features can be dated by varve chronology, which in turn would provide bracketing ages for the build-up and demise of the Coire Ardair and Ossian LLR glaciers respectively. The timing of the latter has wider significance, in view of the proposals made by Bromley et al. (2014), referred to in the preceding section. It is also possible that more subtle links may emerge from closer inspection of the sedimentological evidence. For example, Jones et al.'s (2017) examination of the moraines deposited by the LLR glacier in Coire Ardair suggests that the glacier retreated in an oscillatory manner, perhaps reflecting short-term climatic perturbations. These might in turn be reflected by changes in the rate and type of sediment delivery to Loch Laggan, the timing of which might be registered in the varve record. If so, a prime target for future research would be to determine whether these match the cyclic variations detected in the LMVC (see section 2.5 and Palmer et al., 2012).

We finish by drawing attention to three enigmas concerning the sequence of events in Glen Roy that have not so far been satisfactorily explained. First is the 334 m shoreline in Glen Roy: this is a discontinuous feature which is faintly etched on to the flanks of some southerly facing slopes, for example on the northern flank of the col between Caol Lairig and Glen Roy (the minor shoreline indicated on Figure 12B) and on the north-eastern flank of Glen Roy, north of the Viewpoint (Figure 1). There is no overflow col that accords with this altitude, and hence the water presumably escaped along the margin of the ice near the Viewpoint, during ice retreat, but for how long is not known. Secondly, there is the problem of the 355 m lake shoreline in Glen Gloy. This remains a puzzle, whichever interpretation is preferred for the maximum position of the LLR glacier in that valley. If the ice did reach the Turret fan (section 3.3), then the shoreline would have to have formed during ice retreat, and it is not clear whether there was sufficient time to achieve this. Furthermore, the 355 m shoreline ends abruptly at point D in Figure 3, which is difficult to place within the scheme of events outlined in Table 2 and Figure 16. Why did the ice retreat from the Turret fan, disappear from upper Glen Roy to enable the 355 m shoreline to form, and then halt at this particular location? On the other hand, if the LLR maximum was located at the down-valley termination of the 355 m shoreline, as Peacock (1986) has maintained, this would mean that the 355 m lake probably persisted in upper Glen Gloy for longer than the 515 years over which the Glen Roy lakes existed. There should therefore be a sequence of varved sediments that reflect this, but no such evidence has yet been found.

The final enigma we consider is one that has wider relevance, and that is whether the Late Devensian/ Dimlington Stadial ice sheet completely disappeared from the Scottish Highlands before renewed glaciation was initiated during the LLS, or whether some vestiges of the ice sheet remained throughout the Lateglacial Interstadial. This is a debate that has rumbled on for more than 40 years (see e.g. Ballantyne and Stone, 2012). Focusing on the Glen Roy area, Figure 13 provides evidence that any ice that may have remained must have been confined to the high mountains of the western Highlands, as undisturbed Lateglacial Interstadial sediments accumulated in the lake basins of Loch Etteridge, Loch Tarff, Pulpit Hill, Salen and several sites on Arisaig. That ice clearly did readvance during the LLS is demonstrated stratigraphically at a number of sites, including close to the southern shores of Loch Lomond (Rose et al., 1988; MacLeod et al., 2011). The question is, where did the ice readvance from? Allied to this question is one of timing: if the ice had disappeared completely from the mountains of the Great Glen, the Ben Nevis range, those encircling Rannoch Moor, the Monadhliath plateau and so on, would there have been sufficient time during the LLS (dated to between 12.9 and 11.7 ka) to generate the volume of ice that led to the impoundment of the Glen Roy lakes, or that extended all the way from the central Highlands to the southern shore of Loch Lomond (Golledge, 2010)? It is an important question, but one that is difficult to address, because ice advance during the LLR would have removed any evidence of this more confined ice stage. This therefore remains a gap in our knowledge, the resolution of which is perhaps in need of inventive field campaigns.

We hope that this synthesis paper gives a flavour of the exciting evidence that is preserved in the Glen Roy area, the insights that it has revealed into the rapid transformation of its landscape at the end of the last glacial stage, and the potential it affords for even deeper insights in the future. The Glen Roy NNR remains one of our national geological and geographical treasures, an ideal outdoor laboratory for teaching future generations of earth scientists at different stages of learning. It also offers huge scope for the education and enlightenment of school pupils and the general public, in aesthetically arresting surroundings. We therefore hope this special issue will encourage others to not only visit the area, but perhaps even to join the challenge of solving the problems and puzzles that have been outlined.

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Figure captions

Figure 1: Figure 1: The Parallel Roads of Glen Roy viewed from Bohuntine Hill, close to the Viewpoint, and facing toward the north-west. The three main shorelines are clearly demarcated while the discontinuous and much less distinct 334 m shoreline is just distinguishable in the central part of the image.

Figure 2: Figure 2: Topographic map of the principal physiographic and drainage features of Glens Roy, Gloy and Spean and their catchments, and of neighbouring areas referred to in this paper, which conditioned the extent and altitudes of glacial lakes impounded by glacial ice that encroached into the area from the west (after Lowe et al., 2008).

Figure 3: Figure 3: Schematic diagram of the distribution and extent of the palaeo-lake shorelines in Lochaber and the location of key ice margin positions (after Lowe et al., 2008).

Figure 4: Figure 4: Schematic diagram of the 260 m lake that developed when ice sourced in the Great Glen and Nevis Range coalesced to form an ice dam in the vicinity of Spean Bridge. The locations of the cols controlling this lake, the 325 and 350 m lakes in Glen Roy, and the 355 m lake in Glen Gloy, are also indicated (modified from Sissons, 2017a).

Figure 5: Figure 5: The maximum extent of the Loch Lomond Readvance in Glen Roy and vicinity (adapted from Sissons, 1979a, 2017a). It should be noted that the ice limits shown in Glens Gloy and Turret are contested, the limits of a plateau icefield inferred for the Carn Dearg area (Boston et al., 2013, Boston and Lukas, 2017) have been omitted, and the maximal positions of ice advance in the different valleys are not thought to have been reached synchronously. These matters are all discussed in the text.

Figure 6: Figure 6: Examples of the variation in microscale structure of varved deposits observed by Palmer et al. (2010; 2012). There are differences in detail, but all show

contrasting grain-size measurements between coarse (summer) and fine-grained (winter) layers.

Figure 7: Figure 7: Variations in the thickness of the varved sediment sequences preserved in Loch Laggan and on the Glen Turret and Burn of Agie fans, on which the Lochaber Master Varve Chronology, which spans an interval of 515 years, is based (from Palmer et al., 2010).

Figure 8: Figure 8: NEXTMap DSM image of Lochaber and adjacent districts, indicating the main topographical features and providing locational context for several of the figures that follow.

Figure 9: Figure 9: NEXTMap DSM image of upper Glen Roy, showing the principal gravel fans and other key features referred to in the text.

Figure 10: Figure 10: NEXTMap DSM image of middle Glen Roy, showing the principal gravel fans and other key features referred to in the text.

Figure 11: Figure 11: A 3D reconstruction of the Carn Dearg plateau icefield, and its connection with the larger Monadhliath Icefield, based on the interpretations of Boston and Lukas (2017).

Figure 12: Figure 12: A. NEXTMap DSM image of the lower Glen Roy catchment, including Caol Lairig, and adjacent Glen Spean. The dashed box indicates the area represented in B. **B.** Geomorphological map of the Caol Lairig valley (after Tye and Palmer, 2017).

Figure 13: **Figure 13**: Location of the sites closest to Glen Roy (located within stippled box) that contain sediment sequences extending to the Lateglacial Interstadial, and which therefore lie outside the limits of the Loch Lomond Readvance. Note that several sites in the vicinity of Arisaig display this type of sequence.

Figure 14: Figure 14: Synthesis of the varve and tephrostratigraphic records currently available from sites in Lochaber and adjacent localities. The age estimates for the tephra layers are based on data published by Timms et al. (2016), Bronk Ramsey et al. (2015) and Pilcher et al. (1996).

Figure 15: Figure 15: A. NEXTMap DSM image of the Loch Laggan catchment, highlighting the locations of the Creag Meagaidh Range and Coire Ardair, the Moy Delta, the Aberarder fan, and the Pattack/Mashie 260 m col. **B.** NEXTMap DSM image of parts of the Glen Spean and Loch Treig catchments, showing the location of the maximum limits of the Treig Glacier and the location of the Inverlair pollen site.

Figure 16: Figure 16: Schematic diagram of the sequence and timing of key stages in the development of the glacial landforms and deposits in Glen Roy and vicinity, based on the evidence discussed in this special issue, and summarised in Table 2. The timing of these events are compared with i) the chronology of events in the only other area in Scotland that has furnished a Loch Lomond Stadial varve chronology, the area adjacent to the southern shores of Loch Lomond (MacLeod et al., 2011); ii) to the new chronological data from Rannoch Moor (Bromley et al, 2014; Small and Fabel, 2016); and iii) the radiocarbon dates and tephra horizons from the Lateglacial sequence of Loch Etteridge in the Truim valley. Cosmogenic radionuclide ages and tephra ages are quoted with 2 sigma age errors. Question marks indicate that the timing of onset and demise of glacier activity in each valley cannot be linked directly to the LMVC.

Table 1: Summary of the different interpretations of the source, limit and age of the last glacier to occupy Glen Turret.

Table 2: A schematic timeline for the sequence of events in Glen Roy and vicinity during the Loch Lomond Stadial/Readvance.

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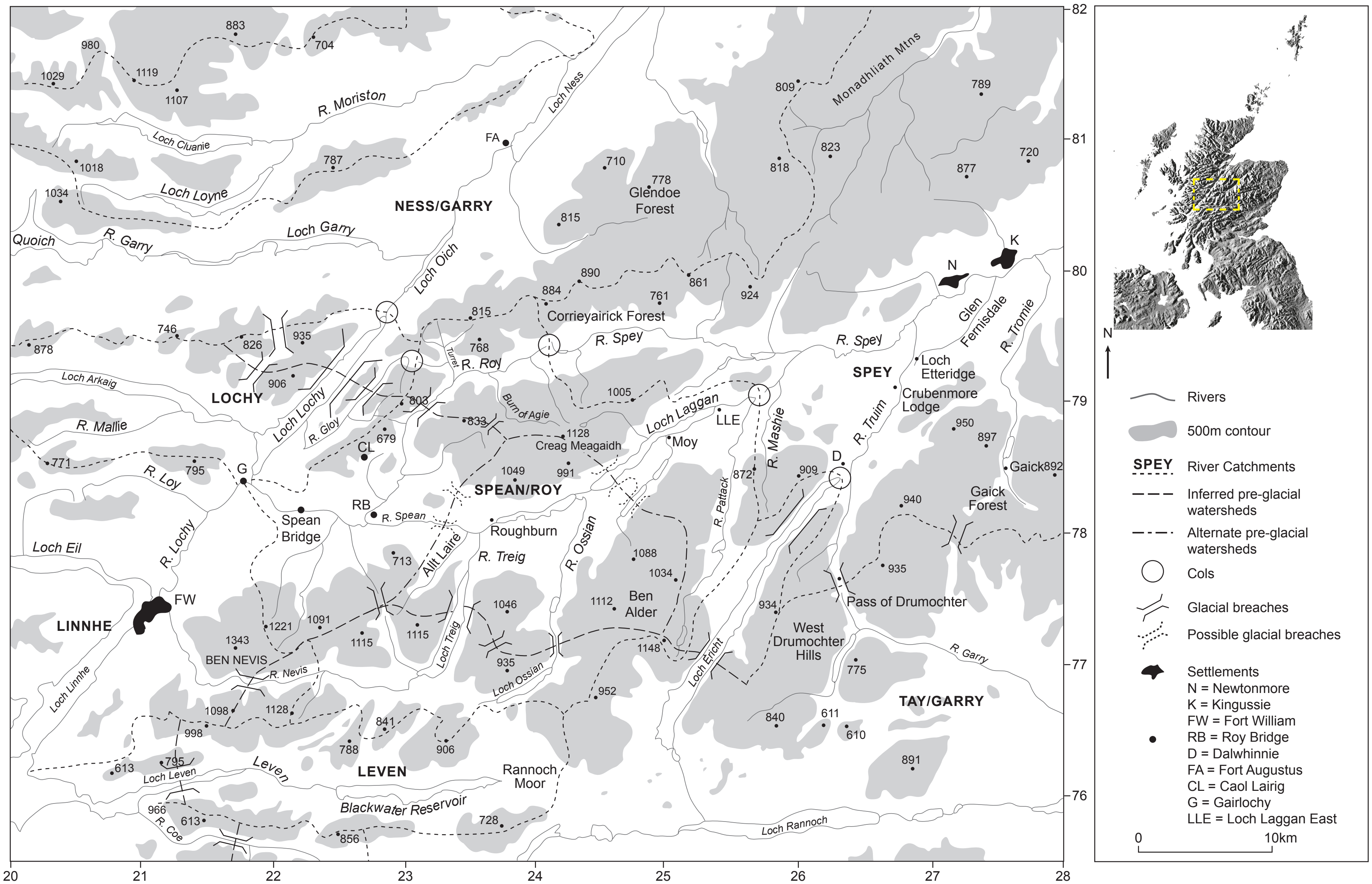
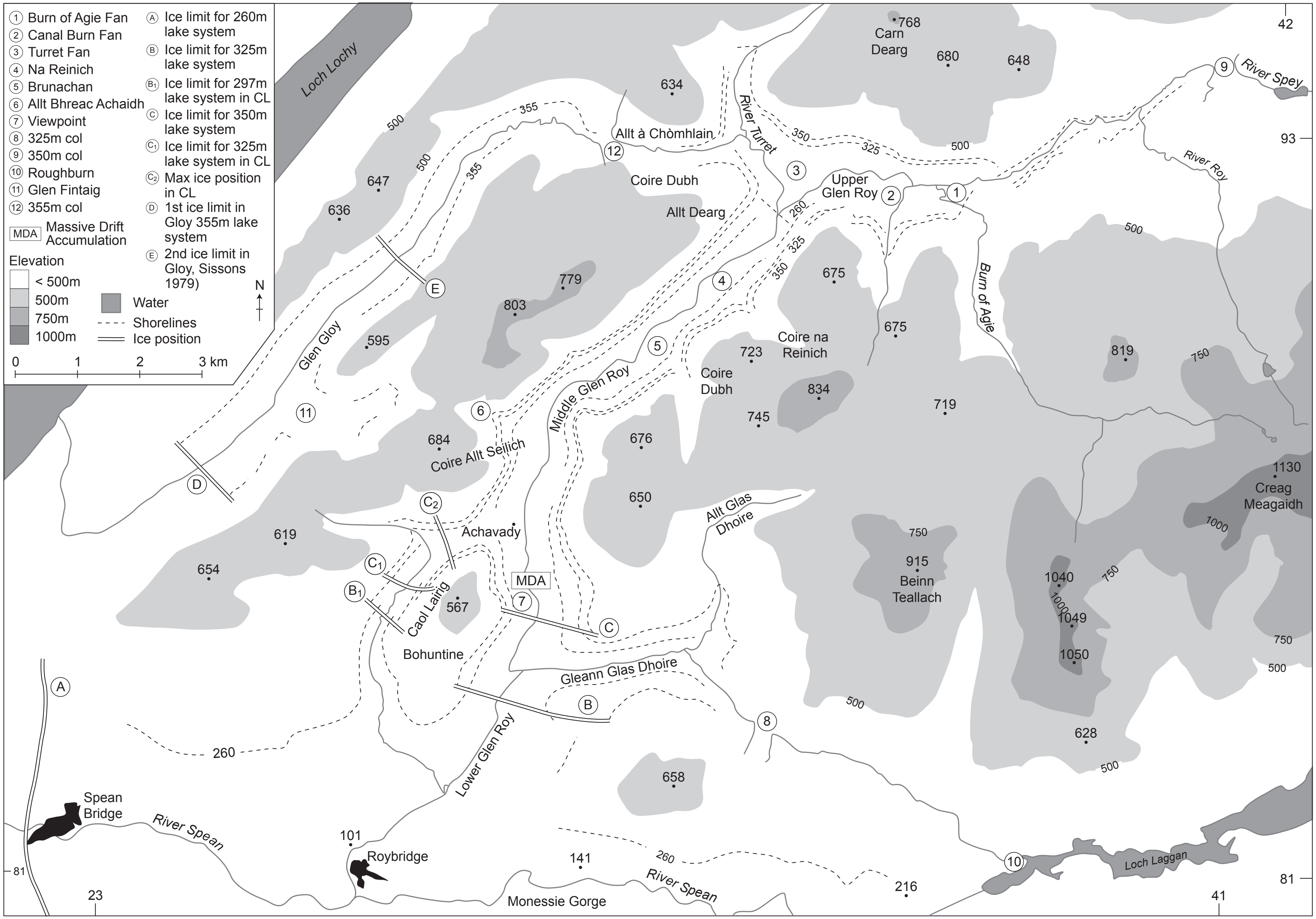
Figure 1

Figure 2



R. Moriston
Loch Ness
Loch Cluanie
Loch Loyne
Loch Garry
Quoich
R. Garry
Loch Oich
NESS/GARRY
FA
Glendoe Forest
Monadhliath Mtns
Corrieyairick Forest
R. Spey
R. Roy
Turret
Burn of Agie
Loch Arkaig
LOCHY
Loch Lochy
R. Gloy
CL
R. Mallie
R. Loy
G
Spean Bridge
RB
R. Spean
Roughburn
SPEAN/ROY
Creag Meagaidh
Loch Laggan
LLE
Moy
R. Mashie
R. Pattack
R. Ossian
R. Treig
Allt Laire
Loch Eil
R. Lochy
FW
LINNHE
Loch Linnhe
BEN NEVIS
R. Nevis
Loch Treig
Loch Ossian
Ben Alder
Loch Ericht
West Drumochter Hills
Pass of Drumochter
R. Truim
D
SPEY
Loch Etteridge
Crubenmore Lodge
Glen Fernisdale
R. Tromie
N
K
Gaick
Gaick Forest
R. Garry
TAY/GARRY
LEVEN
Loch Leven
Leven
R. Coe
Blackwater Reservoir
Rannoch Moor
Loch Rannoch
Rivers
500m contour
SPEY River Catchments
Inferred pre-glacial watersheds
Alternate pre-glacial watersheds
Cols
Glacial breaches
Possible glacial breaches
Settlements
N = Newtonmore
K = Kingussie
FW = Fort William
RB = Roy Bridge
D = Dalwhinnie
FA = Fort Augustus
CL = Caol Lairig
G = Gairlochy
LLE = Loch Laggan East
0 10km
N

Figure 3



1 Burn of Agie Fan
2 Canal Burn Fan
3 Turret Fan
4 Na Reinich
5 Brunachan
6 Allt Bhreac Achaidh
7 Viewpoint
8 325m col
9 350m col
10 Roughburn
11 Glen Fintaig
12 355m col
MDA Massive Drift Accumulation
A Ice limit for 260m lake system
B Ice limit for 325m lake system
B1 Ice limit for 297m lake system in CL
C Ice limit for 350m lake system
C1 Ice limit for 325m lake system in CL
C2 Max ice position in CL
D 1st ice limit in Gloy 355m lake system
E 2nd ice limit in Gloy, Sissons 1979)
Elevation
< 500m
500m
750m
1000m
Water
Shorelines
Ice position
N
0 1 2 3 km
Loch Lochy
Glen Gloy
Allt à Chòmhlain
Coire Dubh
Allt Dearg
River Turret
Upper Glen Roy
Carn Dearg
River Spey
River Roy
Burn of Agie
Middle Glen Roy
Coire na Reinich
Coire Allt Seilich
Achavady
Allt Glas Dhoire
Caol Lairig
Bohuntine
Gleann Glas Dhoire
Lower Glen Roy
Beinn Teallach
Creag Meagaidh
Spean Bridge
River Spean
Roybridge
Monessie Gorge
Loch Laggan

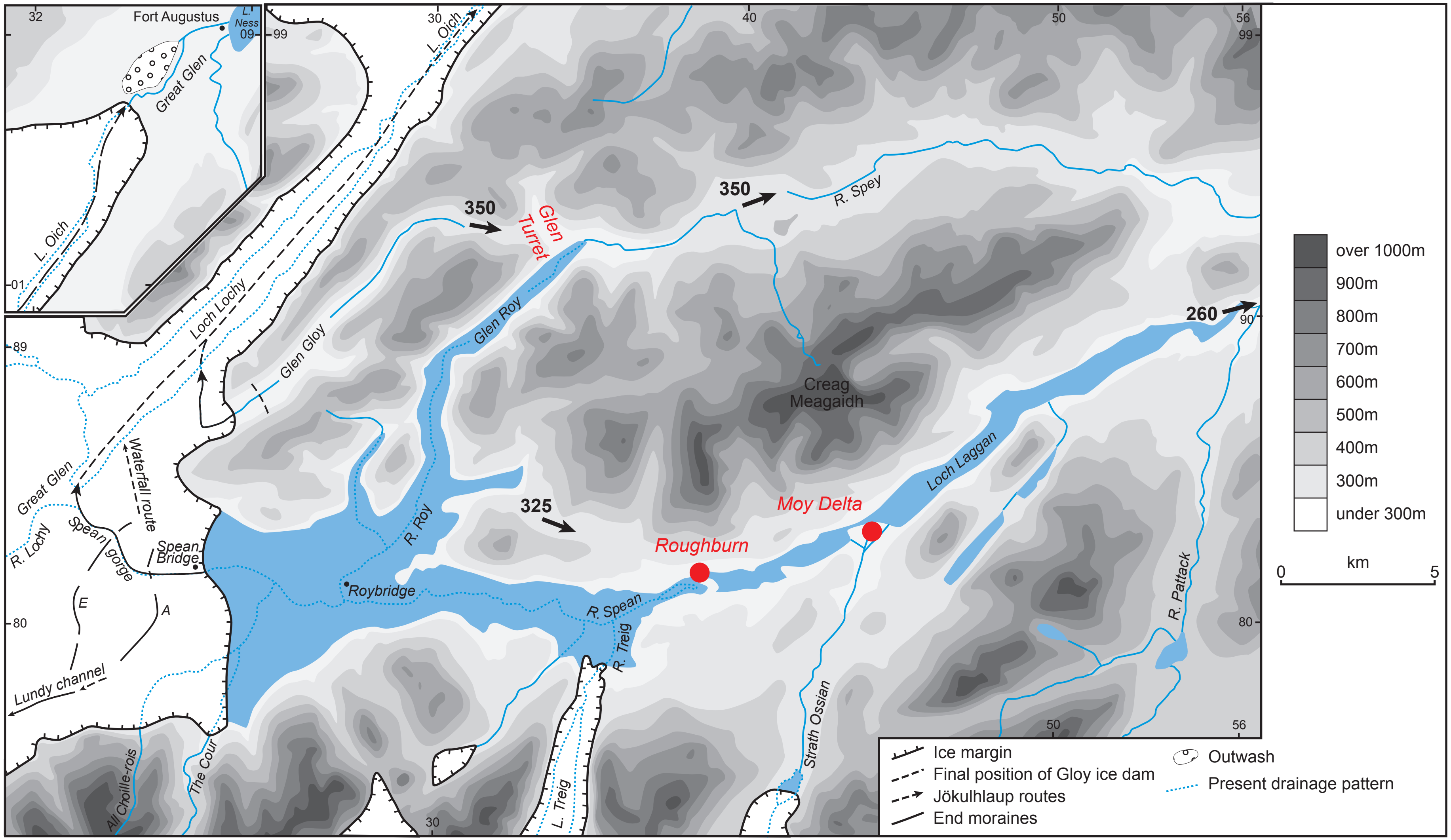
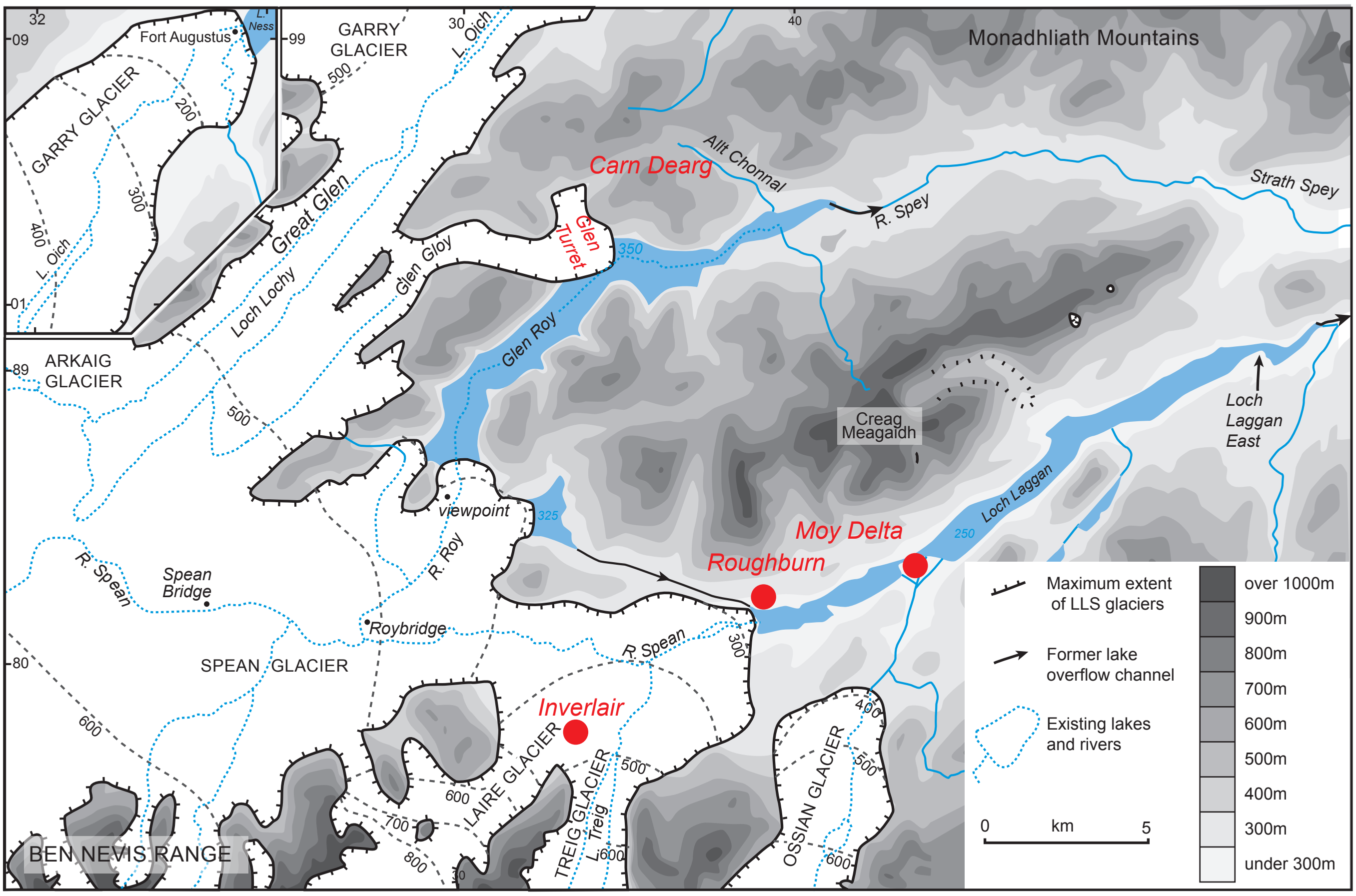

Fort Augustus
L. Ness
Great Glen
L. Oich
Loch Lochy
Glen Gloy
Glen Roy
Glen Turret
R. Roy
350
350
325
260
R. Spey
Creag Meagaidh
Moy Delta
Roughburn
Loch Laggan
R. Spean
R. Treig
L. Treig
Roybridge
Spean Bridge
Spean gorge
Waterfall route
Great Glen
R. Lochy
Lundy channel
E
A
The Cour
Allt Choille-rois
Strath Ossian
R. Pattack
over 1000m
900m
800m
700m
600m
500m
400m
300m
under 300m
km
0
5
Ice margin
Final position of Gloy ice dam
Jökulhlaup routes
End moraines
Outwash
Present drainage pattern

Figure 24



Monadhliath Mountains
GARRY GLACIER
Fort Augustus
L. Ness
GARRY GLACIER
L. Oich
Great Glen
Loch Lochy
Glen Gloy
Glen Roy
Carn Dearg
Glen Turret
Allt Chonnal
R. Spey
Strath Spey
Creag Meagaidh
Loch Laggan
Loch Laggan East
ARKAIG GLACIER
viewpoint
R. Roy
R. Spean
Spean Bridge
Roybridge
Moy Delta
Roughburn
R Spean
SPEAN GLACIER
Inverlair
LAIRE GLACIER
TREIG GLACIER
L. Treig
OSSIAN GLACIER
BEN NEVIS RANGE
Maximum extent of LLS glaciers
Former lake overflow channel
Existing lakes and rivers
0 km 5
over 1000m
900m
800m
700m
600m
500m
400m
300m
under 300m

Figure 7

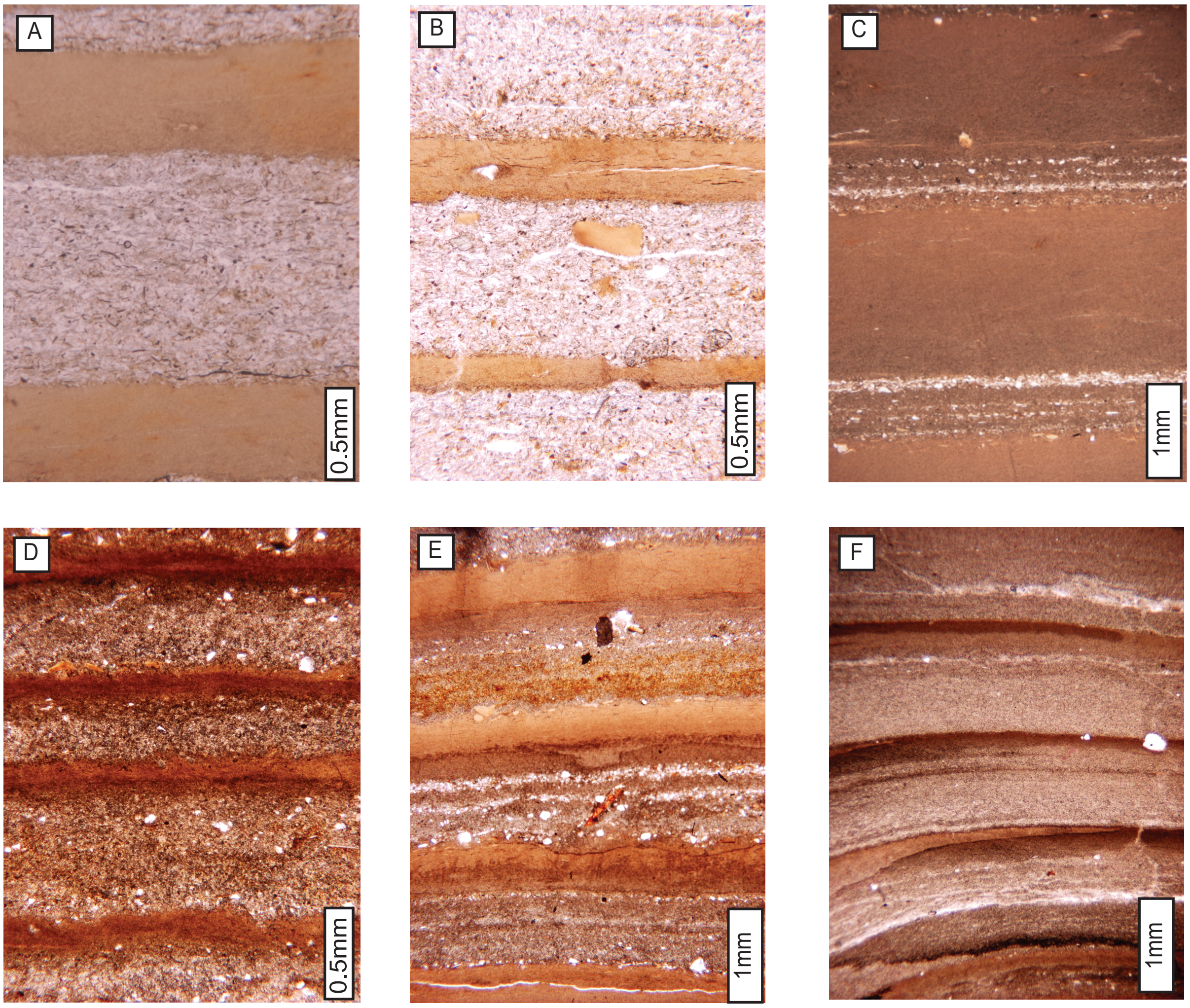
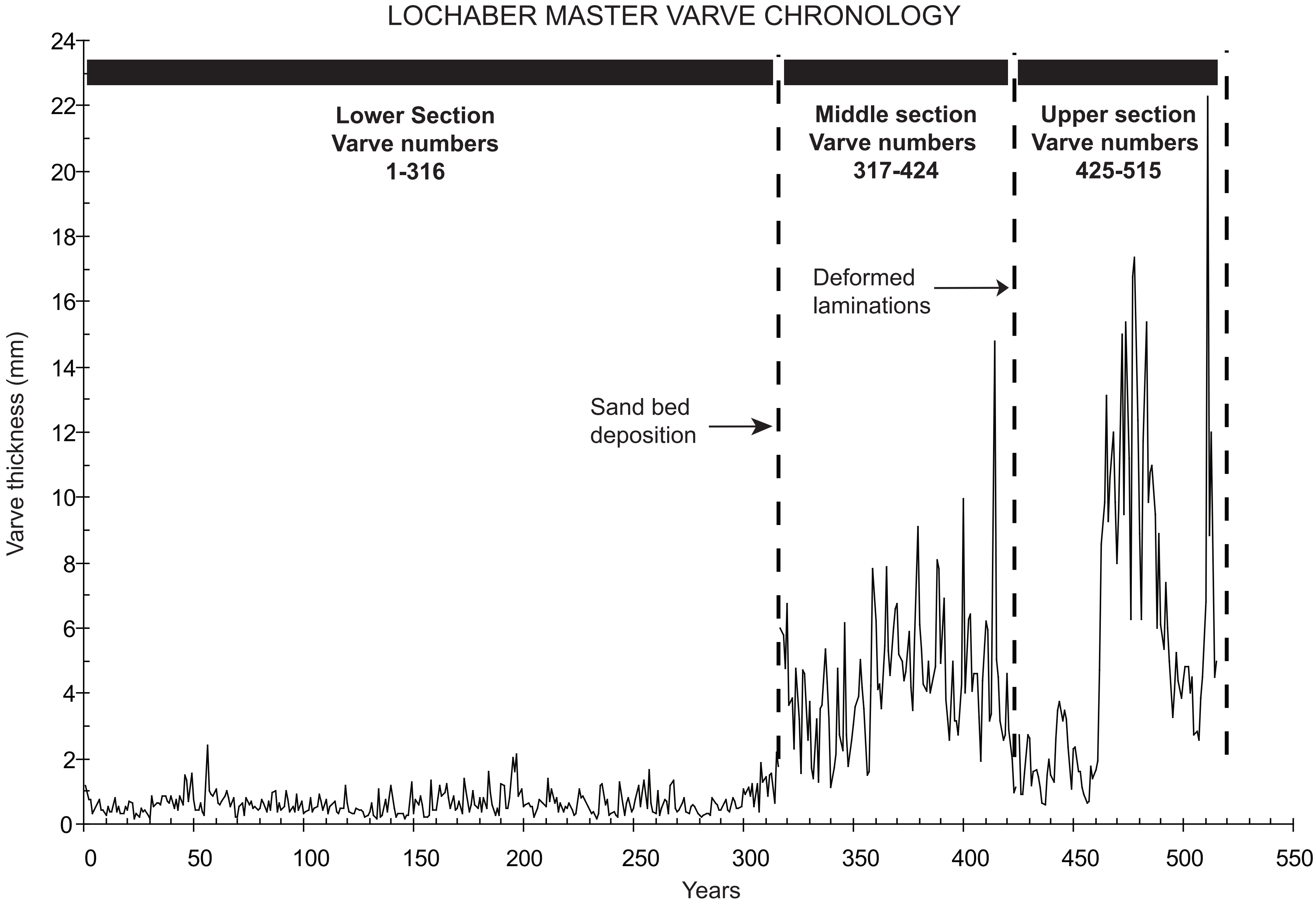


Figure 7



LOCHABER MASTER VARVE CHRONOLOGY
Lower Section
Varve numbers
1-316
Middle section
Varve numbers
317-424
Upper section
Varve numbers
425-515
Deformed
laminations
Sand bed
deposition
Varve thickness (mm)
Years
0
2
4
6
8
10
12
14
16
18
20
22
24
0
50
100
150
200
250
300
350
400
450
500
550

Figure 8

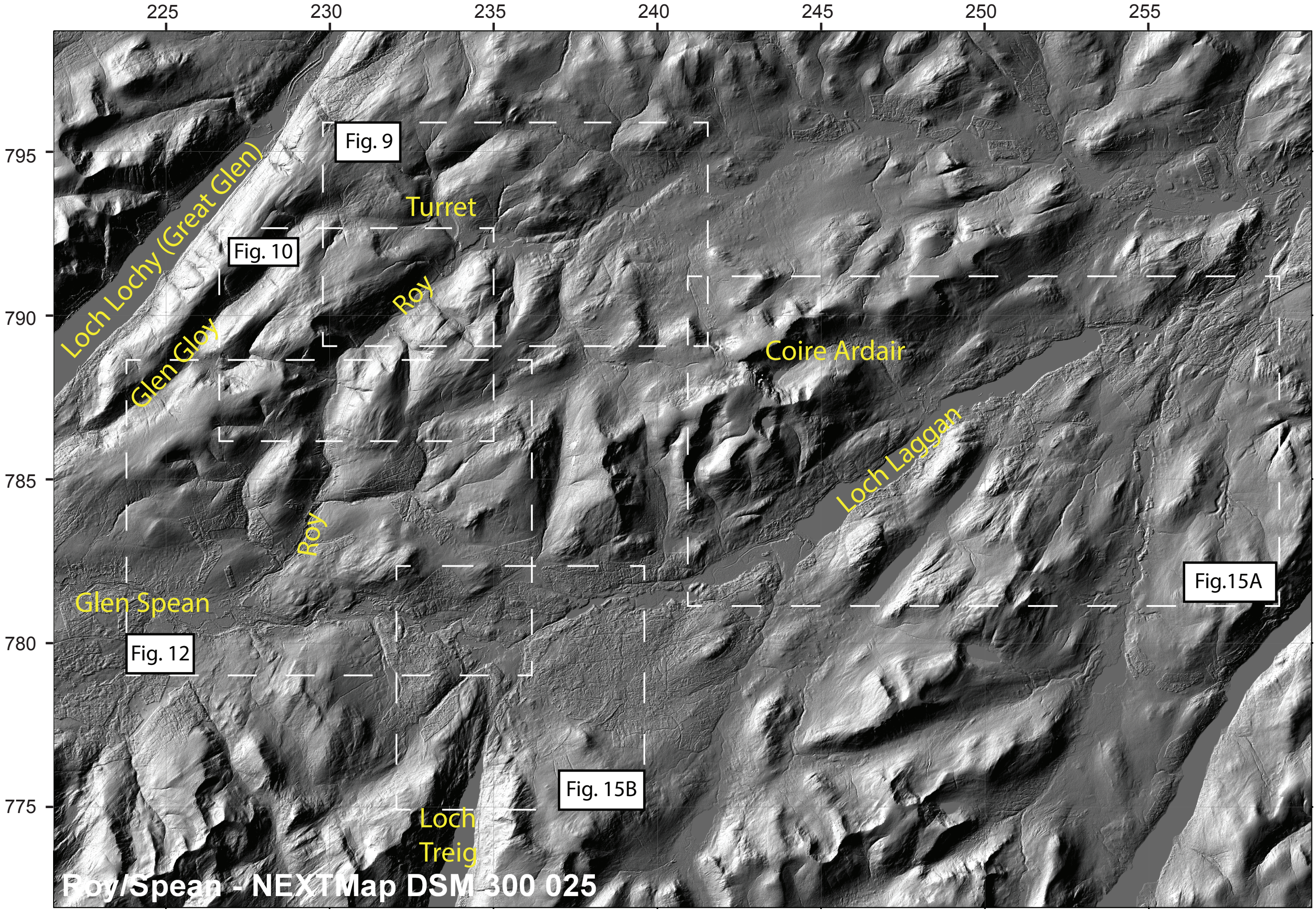

225
230
235
240
245
250
255
795
790
785
780
775
Fig. 9
Turret
Fig. 10
Loch Lochy (Great Glen)
Roy
Glen Gloy
Coire Ardair
Loch Laggan
Roy
Glen Spean
Fig.15A
Fig. 12
Fig. 15B
Loch
Treig
Roy/Spean - NEXTMap DSM 300 025

Figure 9

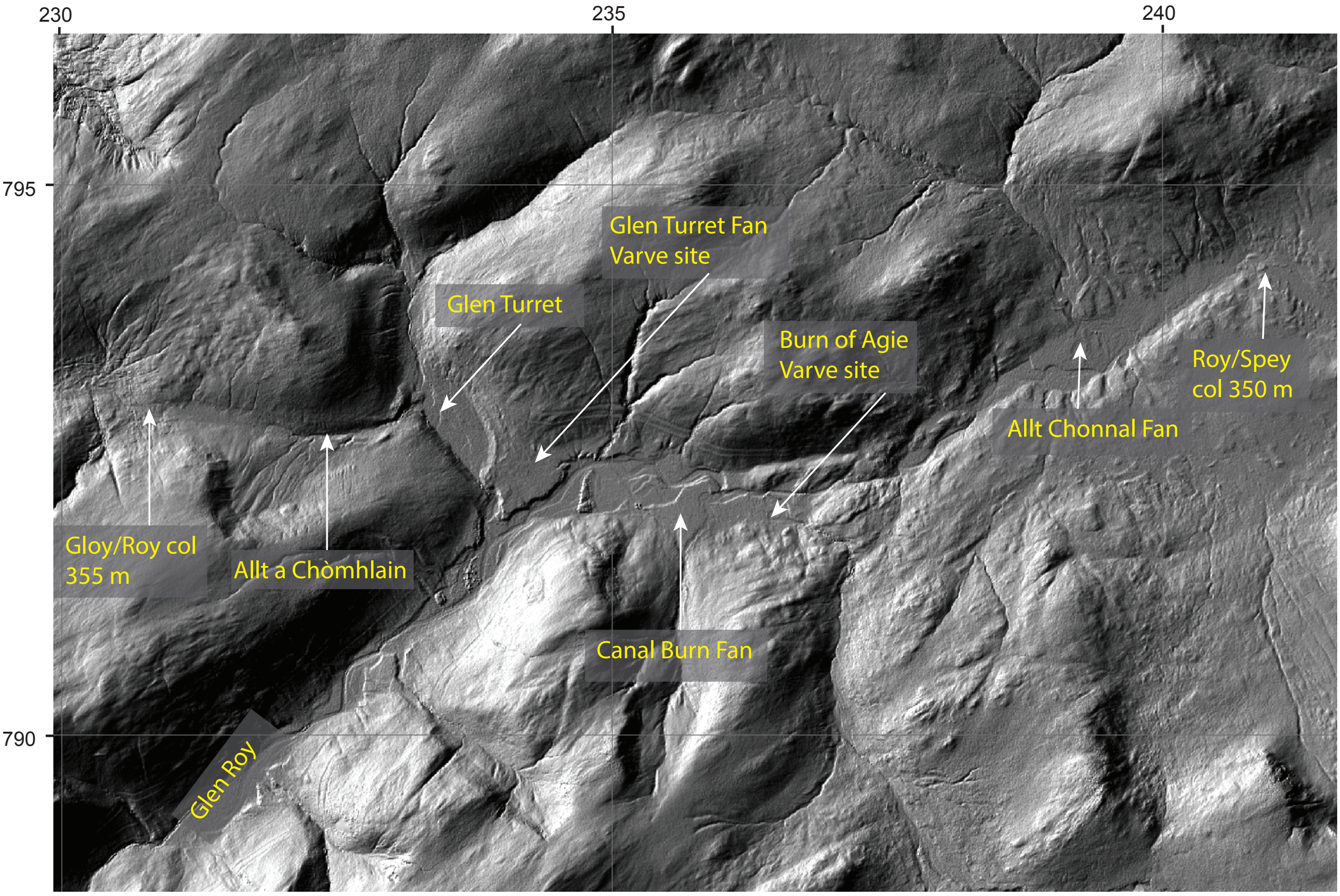

230
235
240
795
790
Glen Turret Fan
Varve site
Glen Turret
Burn of Agie
Varve site
Roy/Spey
col 350 m
Allt Chonnal Fan
Gloy/Roy col
355 m
Allt a Chòmhlain
Canal Burn Fan
Glen Roy

Figure 10

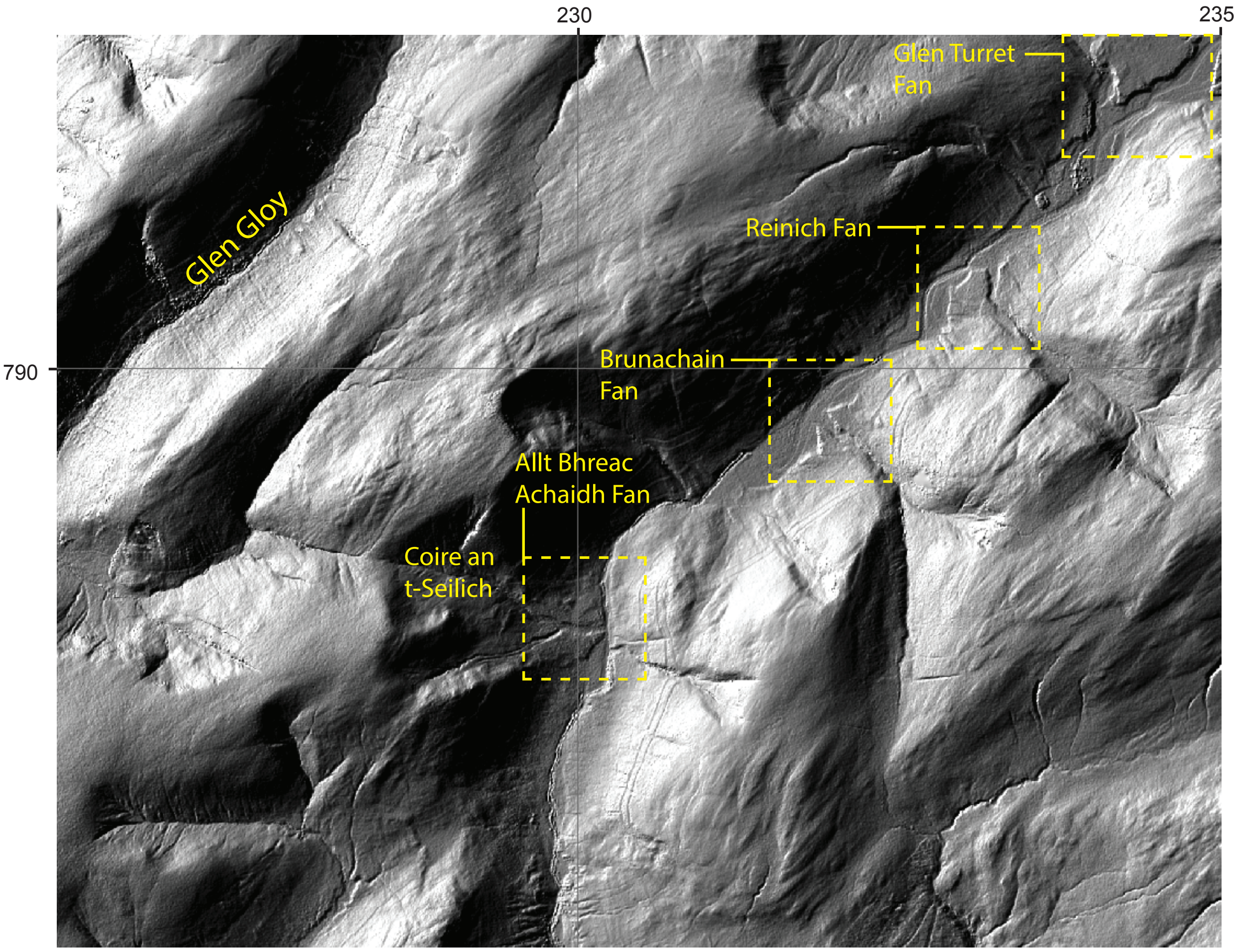
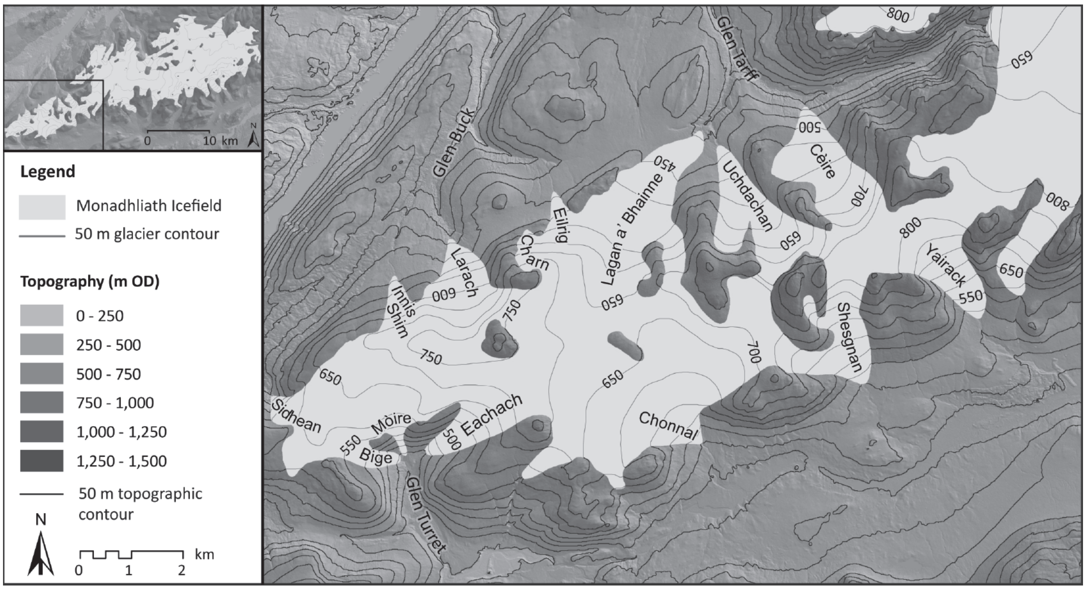
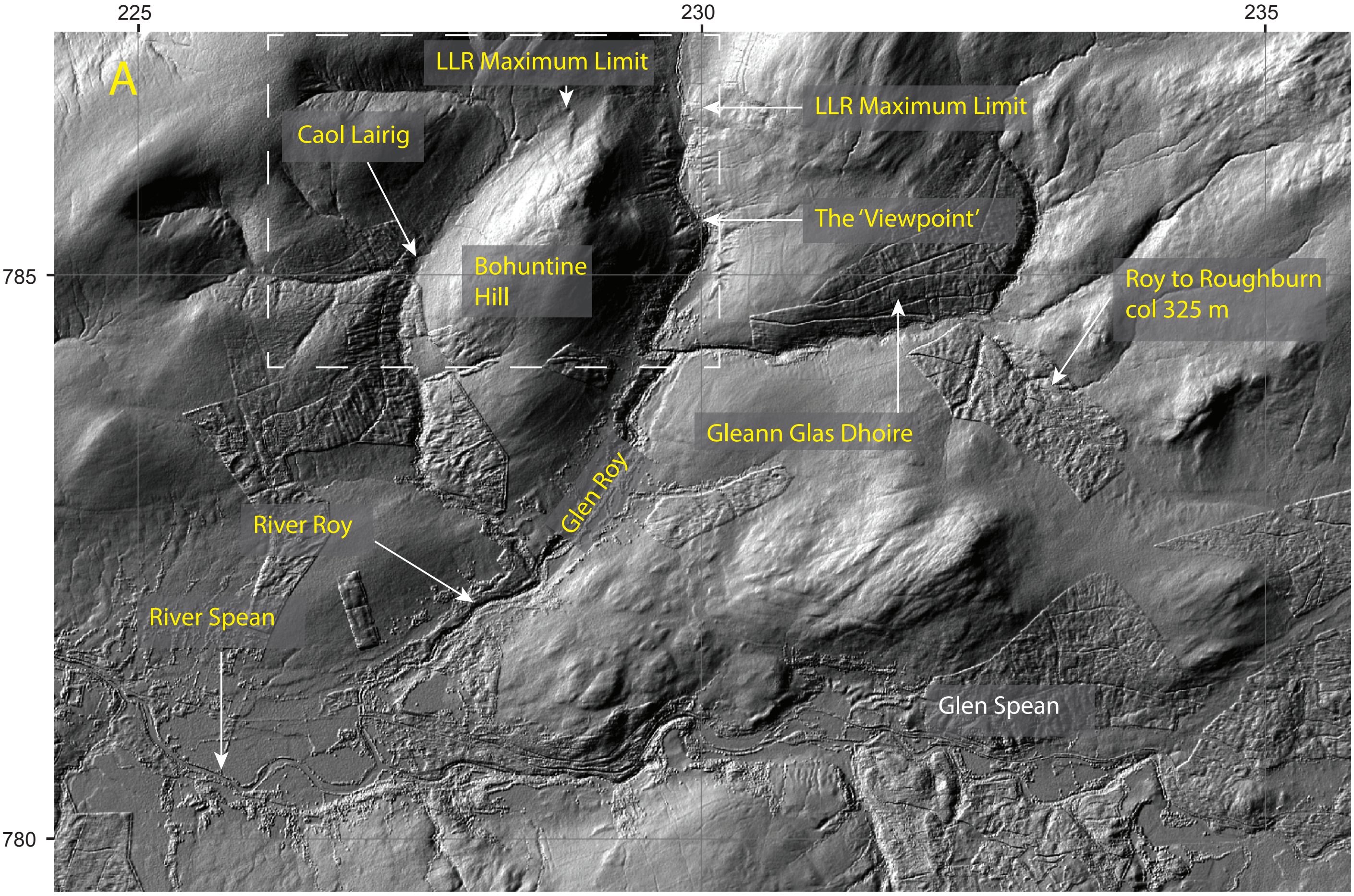

230
235
790
Glen Gloy
Glen Turret
Fan
Reinich Fan
Brunachain
Fan
Allt Bhreac
Achaidh Fan
Coire an
t-Seilich

Figure 11



0
10 km
N
Legend
Monadhliath Icefield
50 m glacier contour
Topography (m OD)
0 - 250
250 - 500
500 - 750
750 - 1,000
1,000 - 1,250
1,250 - 1,500
50 m topographic contour
N
0
1
2
km
Glen Tarff
Glen Buck
Glen Turret
Lagan a' Bhainne
Uchdachan
Cèire
Eilrig
Charn
Larach
Innis Shim
Sidhean
Mòire
Bige
Eachach
Chonnal
Shesgnan
Yairack

Figure 12


225
230
235
785
780
A
LLR Maximum Limit
LLR Maximum Limit
Caol Lairig
The 'Viewpoint'
Bohuntine Hill
Roy to Roughburn col 325 m
Gleann Glas Dhoire
Glen Roy
River Roy
River Spean
Glen Spean

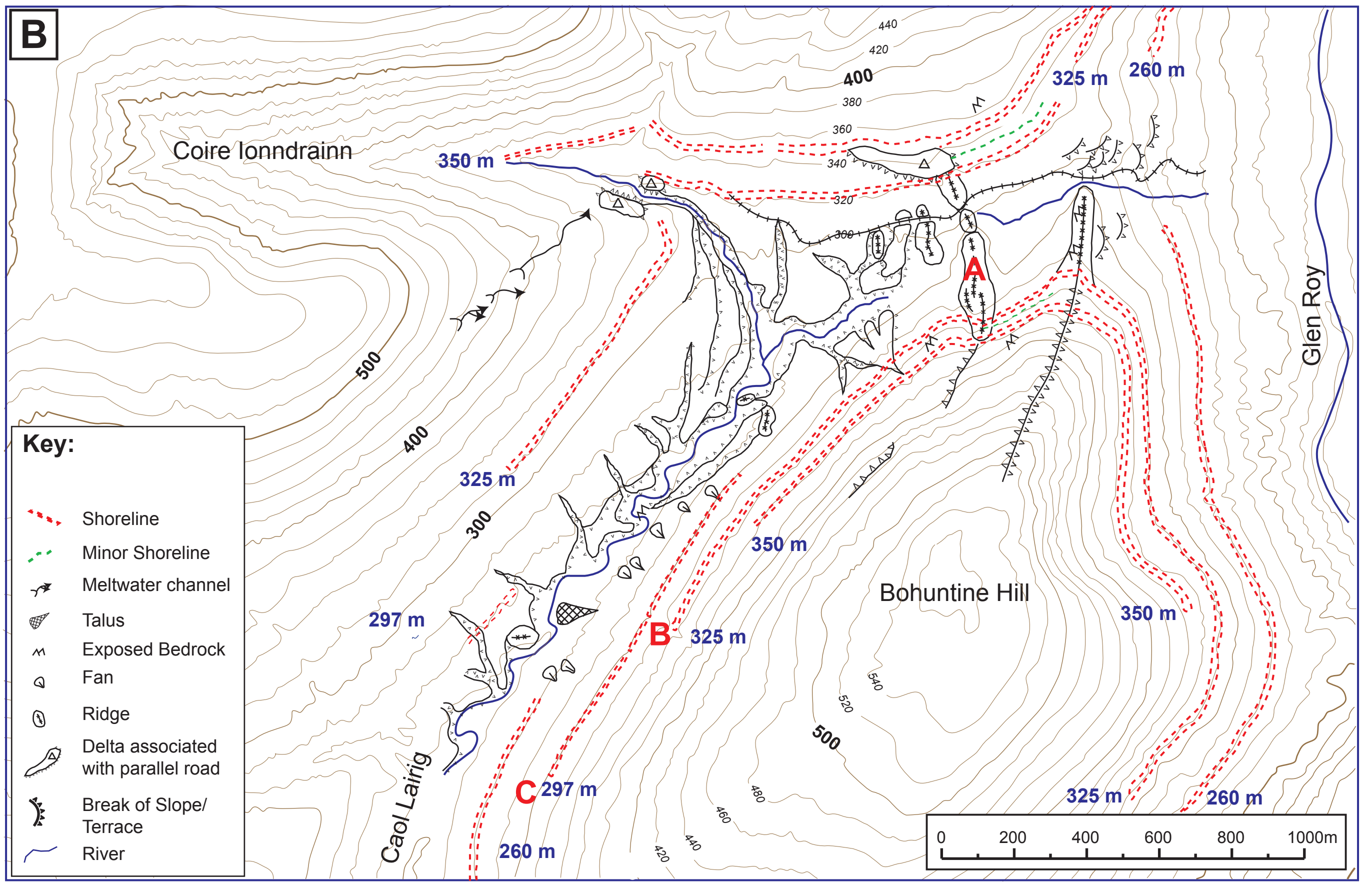
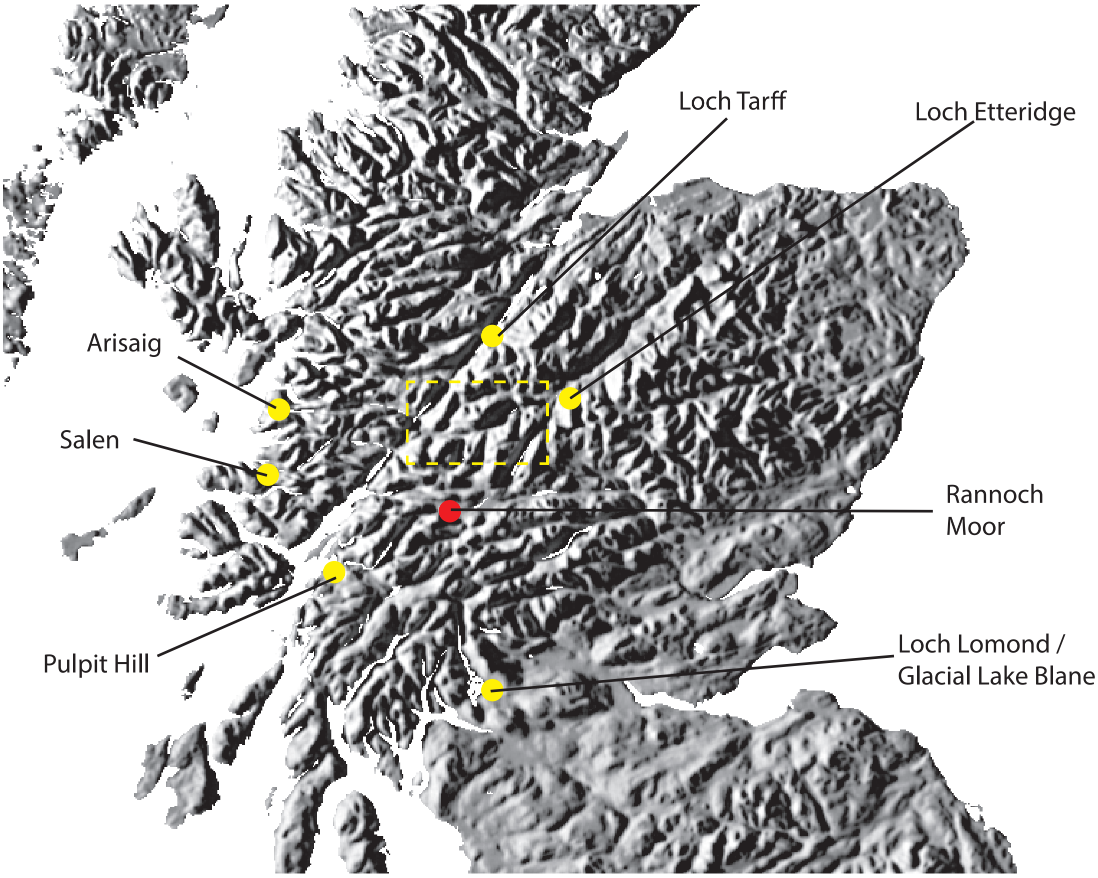
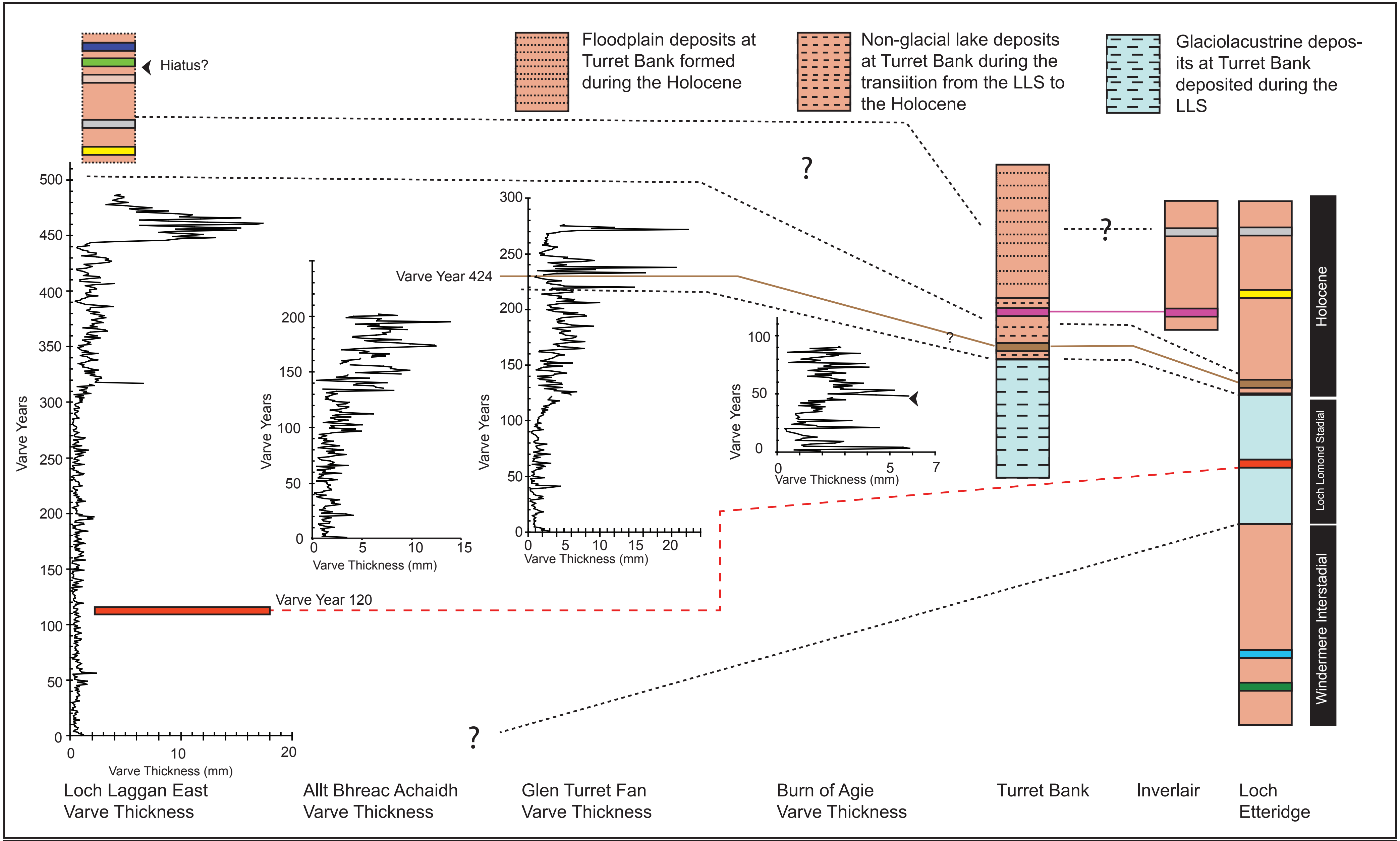

B
Coire Ionndrainn
350 m
325 m
260 m
400
500
400
300
325 m
350 m
297 m
B
325 m
C 297 m
260 m
Caol Lairig
A
Bohuntine Hill
350 m
325 m
260 m
Glen Roy
500
Key:
Shoreline
Minor Shoreline
Meltwater channel
Talus
Exposed Bedrock
Fan
Ridge
Delta associated with parallel road
Break of Slope/ Terrace
River
0 200 400 600 800 1000m

Figure 13

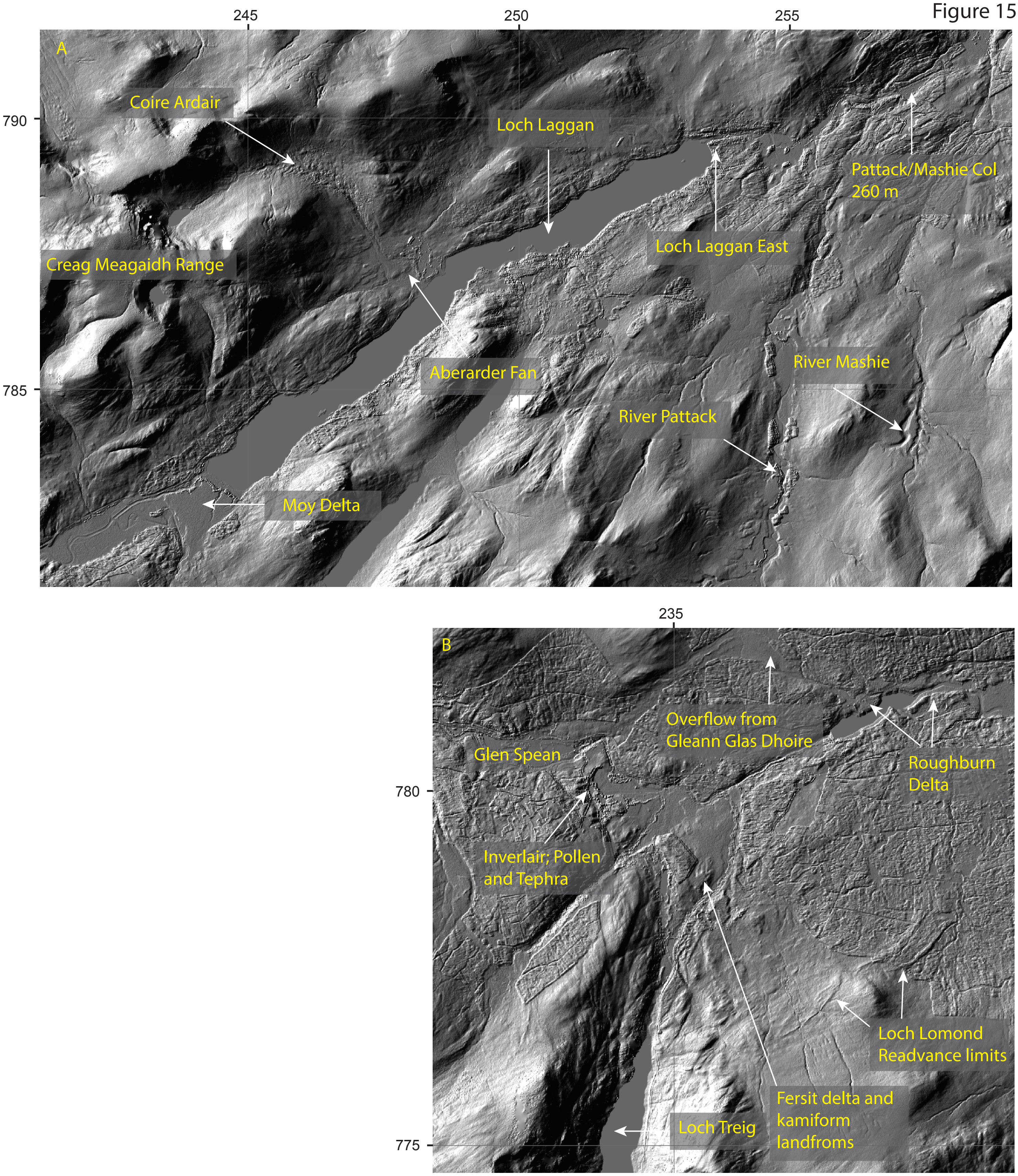

Loch Tarff
Loch Etteridge
Arisaig
Salen
Rannoch Moor
Pulpit Hill
Loch Lomond / Glacial Lake Blane

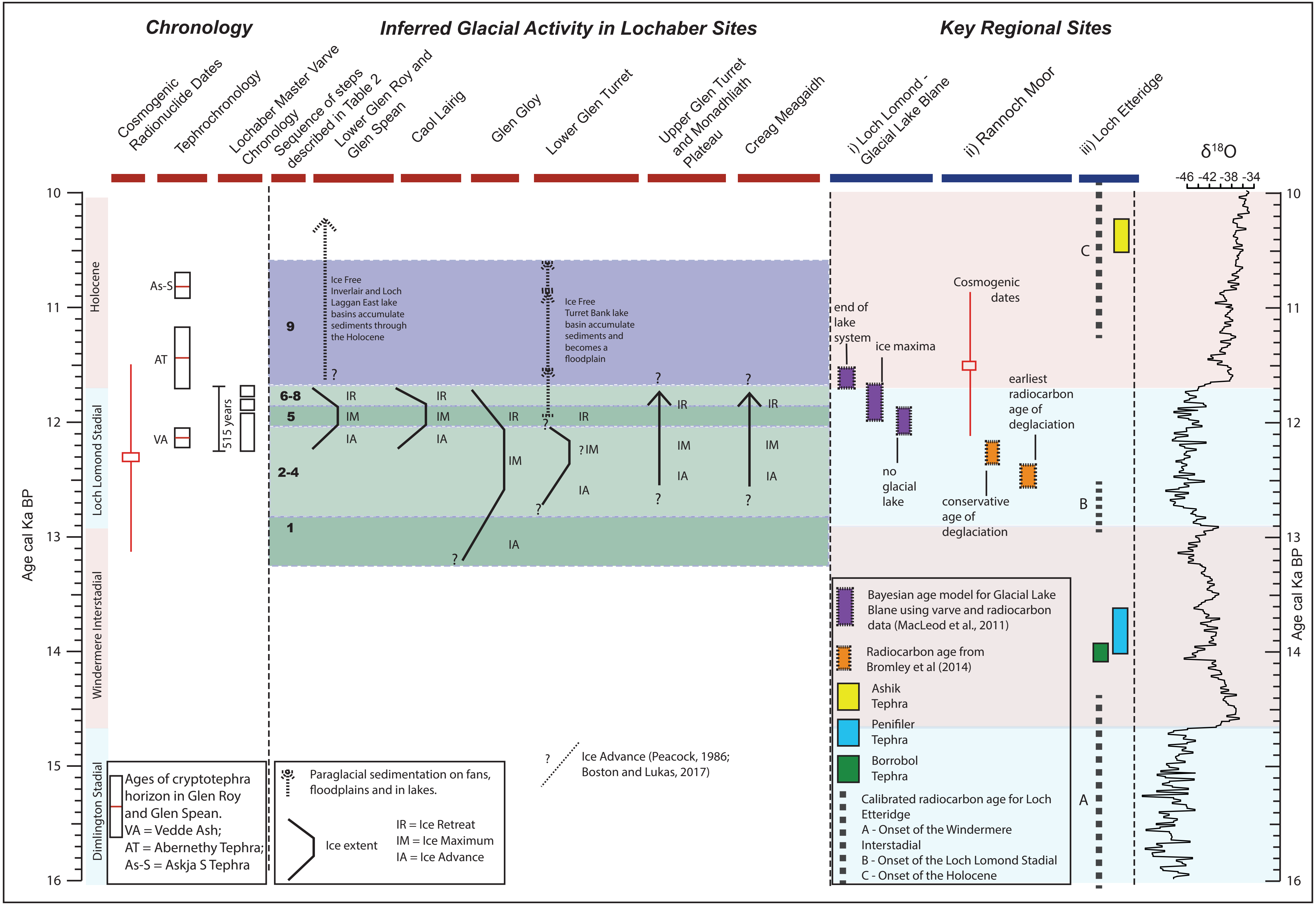


Key for cryptotephra horizons:

- Lairg B 6.72 - 6.63 ka cal BP
- Lairg A 6.95 - 6.82 ka cal BP
- SsnTephra 9.43 - 9.38 ka cal BP
- An DruimTephra 9.77 - 9.57 ka cal BP
- AshikTephra 10.55- 10.25 ka cal BP
- Askja-S/10kaTephra 10.96-10.72 ka cal BP
- Abernethy Tephra 11.7-11.2 ka cal BP
- Vedde Ash 12, 141 yrs BP
- Penifiler Tephra 14.09-13.65 ka cal BP
- Borrobol Tephra 14.14 - 13.95 ka cal BP

Figure 15


245
250
255
790
785
A
Coire Ardair
Loch Laggan
Pattack/Mashie Col
260 m
Creag Meagaidh Range
Loch Laggan East
Aberarder Fan
River Mashie
River Pattack
Moy Delta
235
B
Overflow from
Gleann Glas Dhoire
Glen Spean
Roughburn
Delta
780
Inverlair; Pollen
and Tephra
Loch Lomond
Readvance limits
Fersit delta and
kamiform
landfroms
Loch Treig
775


Chronology
Inferred Glacial Activity in Lochaber Sites
Key Regional Sites
Cosmogenic Radionuclide Dates
Tephrochronology
Lochaber Master Varve Chronology
Sequence of steps described in Table 2
Lower Glen Roy and Glen Spean
Caol Lairig
Glen Gloy
Lower Glen Turret
Upper Glen Turret and Monadhliath Plateau
Creag Meagaidh
i) Loch Lomond - Glacial Lake Blane
ii) Rannoch Moor
iii) Loch Etteridge
δ18O
-46 -42 -38 -34
Age cal Ka BP
10
11
12
13
14
15
16
Holocene
Loch Lomond Stadial
Windermere Interstadial
Dimlington Stadial
As-S
AT
VA
515 years
9
6-8
5
2-4
1
Ice Free Inverlair and Loch Laggan East lake basins accumulate sediments through the Holocene
Ice Free Turret Bank lake basin accumulate sediments and becomes a floodplain
IR
IM
IA
? IM
?
end of lake system
ice maxima
no glacial lake
Cosmogenic dates
earliest radiocarbon age of deglaciation
conservative age of deglaciation
A
B
C
Ages of cryptotephra horizon in Glen Roy and Glen Spean.
VA = Vedde Ash;
AT = Abernethy Tephra;
As-S = Askja S Tephra
Paraglacial sedimentation on fans, floodplains and in lakes.
Ice extent
IR = Ice Retreat
IM = Ice Maximum
IA = Ice Advance
Ice Advance (Peacock, 1986; Boston and Lukas, 2017)
Bayesian age model for Glacial Lake Blane using varve and radiocarbon data (MacLeod et al., 2011)
Radiocarbon age from Bromley et al (2014)
Ashik Tephra
Penifiler Tephra
Borrobol Tephra
Calibrated radiocarbon age for Loch Etteridge
A - Onset of the Windermere Interstadial
B - Onset of the Loch Lomond Stadial
C - Onset of the Holocene